



that policy makers may consider whether a change to a smaller cut-point should be considered. This is especially important in view of the possibility of a major increase in both research measurements, exposure assessment, and regulatory monitoring of fine particles, as well as of PM_{10} .

3.7.2 Size Measurements

Information on the size of fine and coarse particles comes from two basic techniques, (1) particle-counting techniques that measure the size of individual particles and convert the particle number distribution to a particle volume distribution and (2) particle-collecting techniques that use aerodynamic separation, collection of material in specific size ranges, and gravimetric or chemical analysis to determine the total mass or the mass of specific components in the size ranges collected. Particle counting has the potential advantages of not causing as much disturbance to the gas/particle equilibrium. However, considerable care must be taken to avoid heating the sample or diluting it with clean or drier air than that present in the atmosphere. With particle counting techniques it may also be possible to avoid problems of particle bounce. However, several expensive and complex instruments are required to cover the desired range of 0.001 to 100 μm . Because sizes can be measured very precisely, the size ranges covered can be very small and an almost continuous function of number versus size can be obtained.

Particle collecting techniques have the advantage of obtaining size-differentiated samples for chemical analysis. The equipment used is simpler and less expensive. However, aerodynamic separation does not provide as distinct a classification by size. Large particles may bounce from their intended collection surface and be counted in smaller size ranges. Also, the requirement for long sampling times may result in averages of distributions that change with time. Particle collection techniques provide a limited number of size cuts and yield discontinuous functions of mass versus particle size.

Both techniques, however, clearly indicate the natural division of ambient air particles into fine and coarse modes with a minimum between 1.0 and 3.0 μm diameter. Size distributions obtained with particle counting techniques tend to show a lower, broader, and more distinct minimum than distributions obtained with particle collection techniques such as impactors. The position of the minimum between the accumulation and coarse mode may vary from study to study. The peak of the fine particle mode tends to increase in size with increasing concentration

and with increasing relative humidity. Several good reviews of particle size distribution are available: physical properties of sulfur aerosols (Whitby, 1978), urban aerosols (Lippmann, 1980), trace elements (Milford and Davidson, 1985), particulate sulfate and nitrate in the atmosphere (Milford and Davidson, 1987), and coarse mode aerosol (Lundgren and Burton, 1995).

3.7.3 Appropriate Display of Size-Distribution Data

Size-distribution data, if not properly displayed, can give misleading information on the position and shape of peaks and valleys and can lead to incorrect conclusions, especially in regard to the position, width, and separation of fine and coarse modes. For this reason many workers use a histogram display obtained as follows. The mass, number, surface, or volume in each size range is divided by the difference of the logarithms of the diameters at the upper D_i and the lower D_{i-1} ends of the size range, and plotted as rectangles of width $\log D_i - \log D_{i-1}$ and height, i.e. $\text{mass} / (\log D_u - \log D_e)$ on a log diameter scale. This is normally shown as $\Delta C / \Delta \log D$, $dM/d \log D$, or normalized, for example, as $\Delta M/M * \Delta \log D$. Such histogram plots are especially useful for impactor data, which normally yield fewer size intervals than particle-counting techniques. Examples of such displays are shown in Figure 3-13 (Wilson et al., 1977) and Figure 3-14a (John et al., 1990). D_{ae} is typically used when the data is presented as aerodynamic diameter and D_p when the data is presented as geometric diameter.

It is frequently desirable to draw a smooth line through the data in order to identify modes and the mass median diameters (MMD) and widths (σ_g) of modes. This can be done by fitting the data to two or more lognormal distributions, as was done in Figure 3-13 (also see Hasan and Dzubay, 1987; and Whitby-DISFIT (TSI, 1993). It is better to use an inversion process, such as originally developed by Twomey, to construct a continuous curve to represent the measurement data as shown in Figure 3-14b (John et al., 1990; Winklmayr et al., 1990). The continuous curve may then be fit to one or more log-normal distributions as shown in Figure 3-14c. However, one must be aware that log-normal distributions may not always provide good fit to actual data (see Figure 3-16). In this type of presentation the area in each rectangle or the area under a portion of a curve is proportional to the mass in

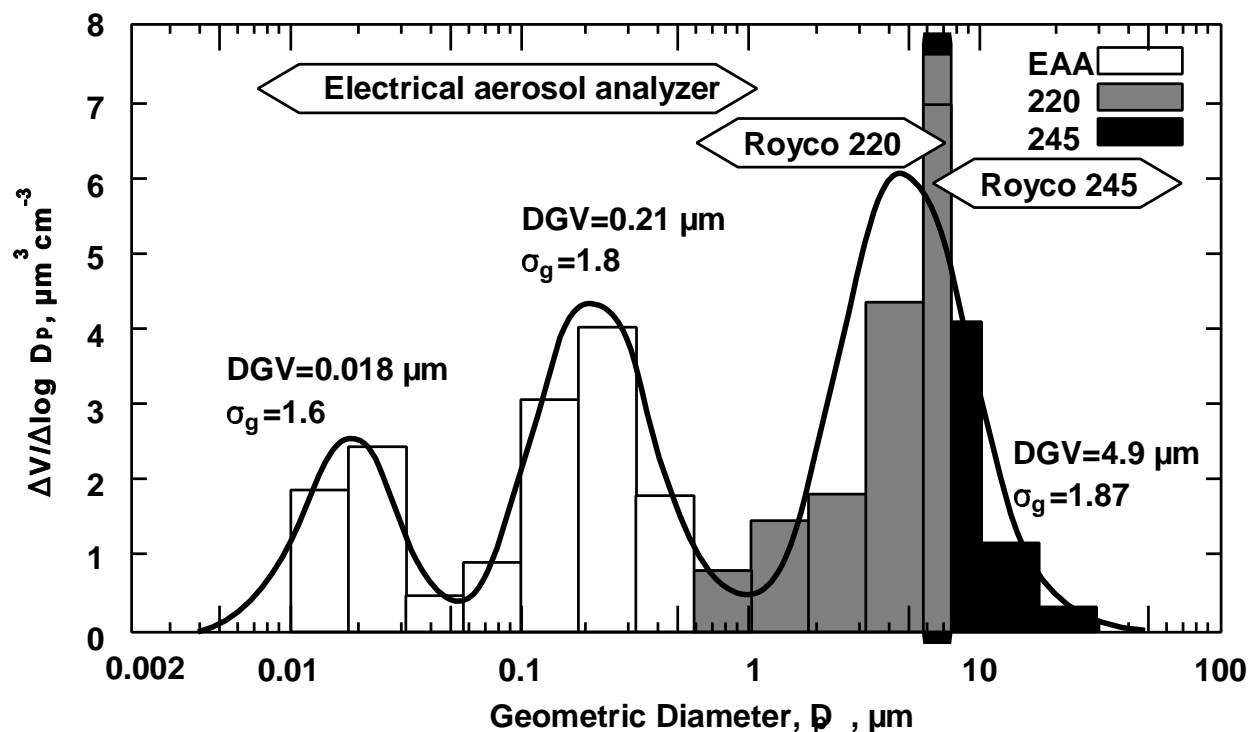


Figure 3-13. An example of histogram display and fitting to log-normal functions for particle-counting size distribution data. Instruments used and the range covered by each are shown. Counts are combined into reasonably-sized bins and displayed. Lognormal functions, fitted to the data, are shown with geometric mean diameter (DGV, equivalent to volume median diameter) of each mode and the width (σ_g) of each mode. Note the clear separation of the nuclei mode (OGV = 0.018 μm), the accumulation mode (OGV = 0.21 μm) and coarse mode (OGV = 4.9 μm). Fine particles, as defined by Whitby (1978), include the nuclei and accumulation mode.

Source: Wilson et al. (1977).

that size range (or the quantity of any other parameter plotted on a linear scale). Plotting mass per impactor stage versus impactor stage number, or drawing lines connecting the midpoints of size range at the heights of the mass in each size range, does not provide such quantitative information. Once the characteristics of the impactor have been demonstrated, and once good fits to lognormal distributions have been obtained, repeated measurements of the same species may be shown by curves fitted to inversion or lognormal distributions such as the example in Figure 3-15 (John et al., 1990).

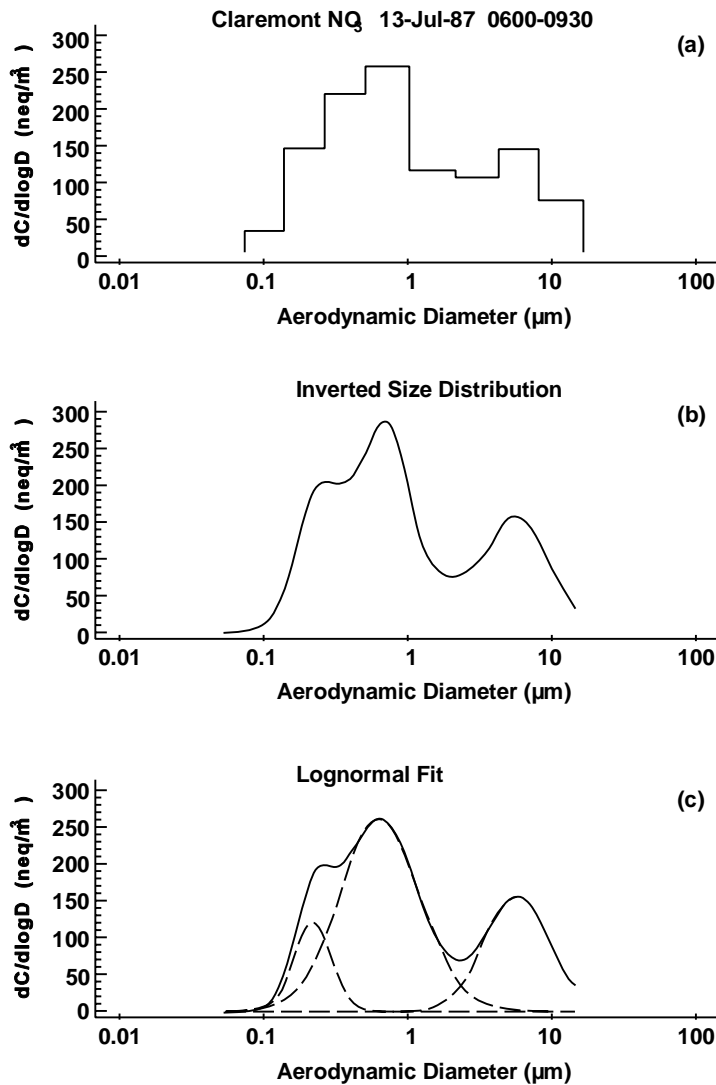


Figure 3-14. An example of an effective display of impactor data: (a) histogram showing mass found on each impactor stage and upper and lower cut points of each stage, (b) inverted size distribution, (i.e., a smooth distribution that would give the observed distribution considering the actual efficiency of each stage; cut points are not exact; each stage allows some large particles, which it should collect, to pass through to the next stage and collects some small particles which it should pass on to the next stage), (c) the solid line is the distribution obtained by fitting a sum of several lognormal functions to the inverted distribution. The dashed lines show the lognormal functions obtained from the fitting process. In this case, the use of log-normal distributions provides a reasonably good fit to the data.

Source: John et al. (1990).

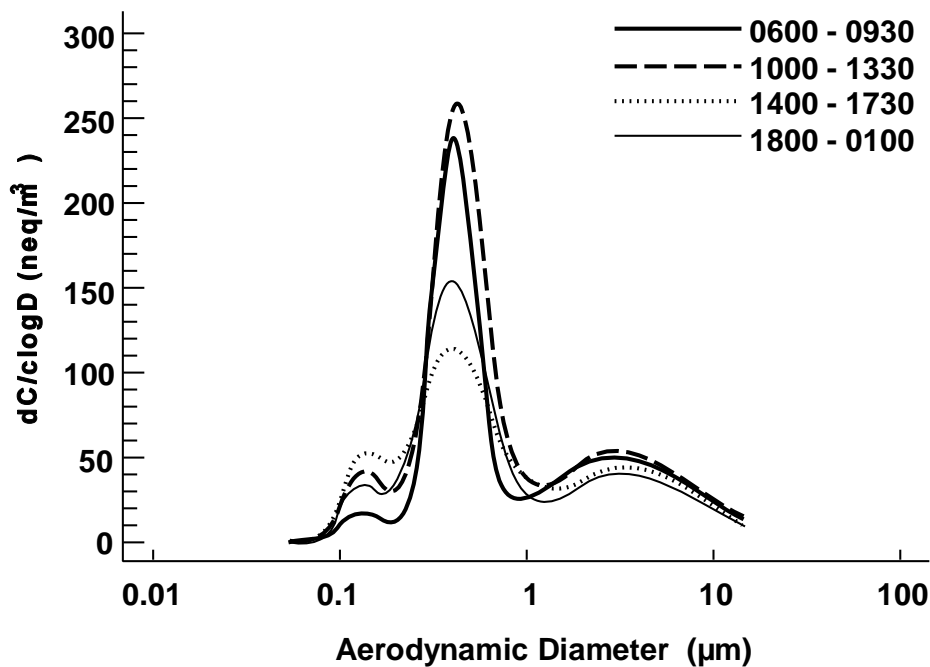


Figure 3-15. Size distributions of sulfate, Long Beach, June, 1987, showing use of fitted log-normal distributions to describe diurnal variations in size and concentration.

Source: John et al. (1990).

In impactor measurements, the maximum size of the upper stage and the minimum size of the lower stage (or after filter) are not well defined. Therefore, an arbitrary choice must be made in order to define the $\Delta \log D_{ae}$. This choice can have a remarkable influence on the perceptions of the positions, height, and width of modes. A particularly dramatic example is shown in Figure 3-16, from Šega and Fugaš (1984). The authors chose $0.1 \mu\text{m}$ for the lower limit and $20 \mu\text{m}$ for the upper limit, suggesting a bimodal distribution with a fine mode MMAD at about $1.5 \mu\text{m}$, and a coarse mode MMAD at about $10.5 \mu\text{m}$. However, if $0.4 \mu\text{m}$ is chosen for the lower limit and $10 \mu\text{m}$ for the upper limit, the display suggests a fine mode MMAD of about $0.7 \mu\text{m}$ and a coarse mode MMAD of about $8 \mu\text{m}$.

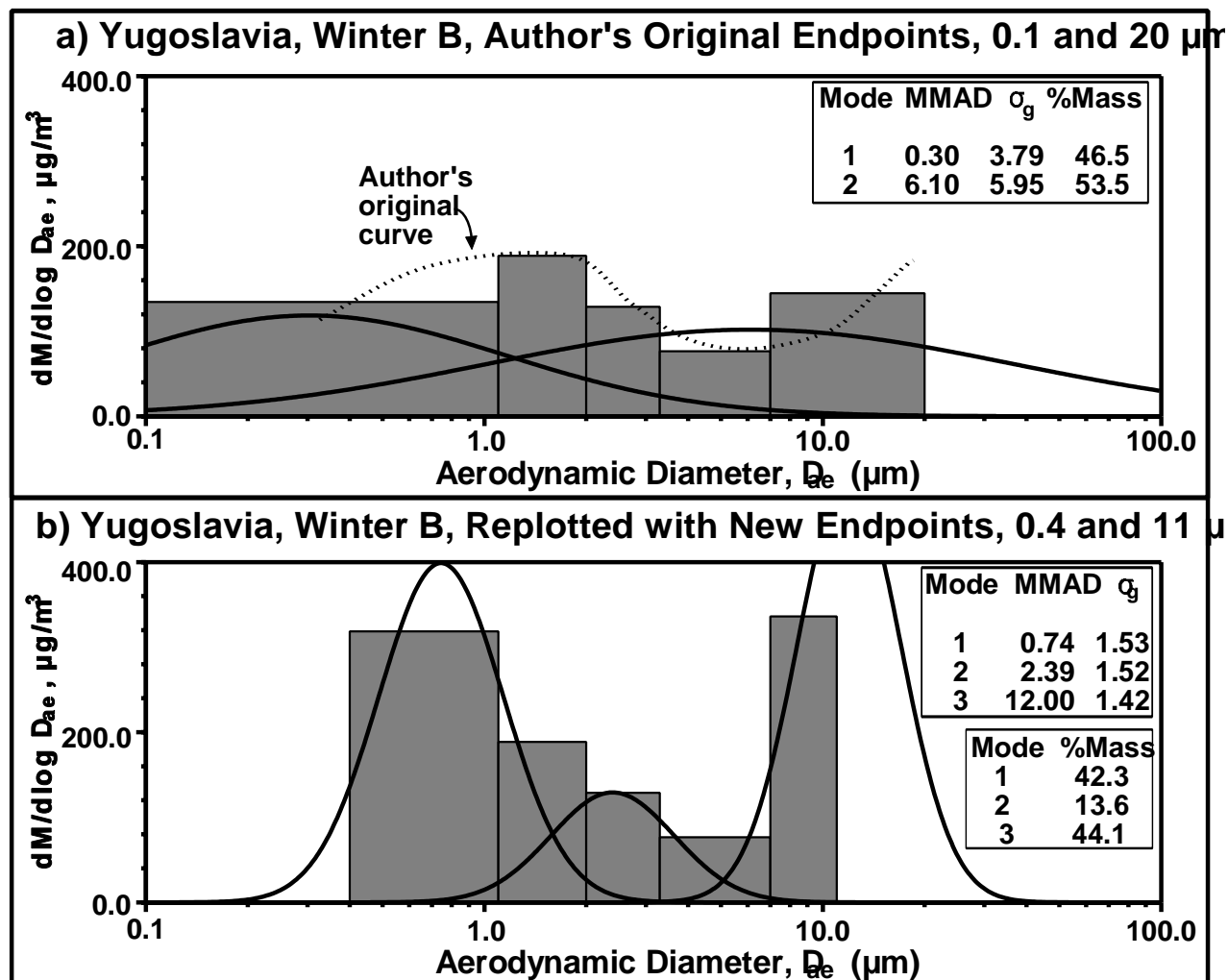


Figure 3-16. Effect of changing endpoints. This example of impactor data shows how the lack of a well-defined upper and lower size limit can affect the perception of the location of fine and coarse particle modes. A histogram with an upper limit of 20 μm and a lower limit of 0.1 μm diameter, along with the curve drawn by authors of the report, is shown in Figure 3-16a. In Figure 3-16b a histogram with a lower limit of 0.4 μm and an upper limit of 10 μm is shown. The author's free hand curve suggests a fine particle MMAD around 1.5 μm diameter. A quite different idea of the location of the modes is given when different endpoints are chosen. Much of the material found between 1.0 and 5.0 μm is probably smaller particles caught on the glass fiber impactor stages which have very poor separation efficiencies. The data has been fitted to a 3-lognormal mode distribution; however, log-normal distributions do not provide a good fit to this data.

Source: Šega and Fugaš (1984).

3.7.4 Comparison of Particle-Counting and Particle-Collection Techniques

Unfortunately, there have been few efforts to compare results of the two particle-sizing techniques. One such effort is shown in Figure 3-17 (Durham et al., 1975). The differences between the two techniques, as evident in the figure, are qualitatively observed in individual studies using either of the two techniques. Particle counting techniques usually give a lower and wider minimum. Typically particle counting leads to volume distributions plotted versus geometric size (or more properly, geometric size inferred from mobility or optical size); whereas impactor separations give mass versus aerodynamic size. In Figure 3-17 both geometric and aerodynamic scales are given. This figure illustrates the problems involved in defining particle "size" and serves as a reminder that each particle sizing technique gives a different "size". The upper scale, used for impactor data, is given in aerodynamic diameter. The aerodynamic diameter of a particle is the diameter of a particle of density, $\rho=1.0$, which would behave similarly with respect to impaction as the particle in question. For spheres in the coarse mode, the aerodynamic diameter, D_a , equals $\sqrt{\rho} D_p$, where ρ is the density of the particle and D_p is the geometric diameter. Since coarse particles are expected to have a greater density than fine particles, converting the volume, geometric-size distribution to a mass, aerodynamic-size distribution would increase the apparent size of the volume distribution above $1 \mu\text{m}$ and widen the minimum. For small particles, below $0.5 \mu\text{m}$, or at reduced pressures where the mean free path of the gas molecules is of the same order, or larger than the particle diameter, the Stokes diameter, which is more closely related to the diffusion coefficient, is a more useful parameter. The relationships between Stokes, aerodynamic and geometric diameter are discussed in Section 3.1.3.1.

The particle size distribution shown on the bottom of the graph was derived from a combination of a mobility counter and several optical counters. The "mobility size", obtained from the electrical aerosol analyzer (EAA) in earlier studies and the differential mobility analyzer (DMA) in more recent studies is dependent on the particle shape but not the density. For irregularly shaped particles the "mobility" size gives the Stokes diameter, which is the geometric diameter of a sphere with the same aerodynamic drag. For a sphere the Stokes diameter and the geometric diameter are the same. By comparing the mobility or Stokes diameter to the aerodynamic diameter it is possible to measure the density of spherical particles (Stein et al., 1994).

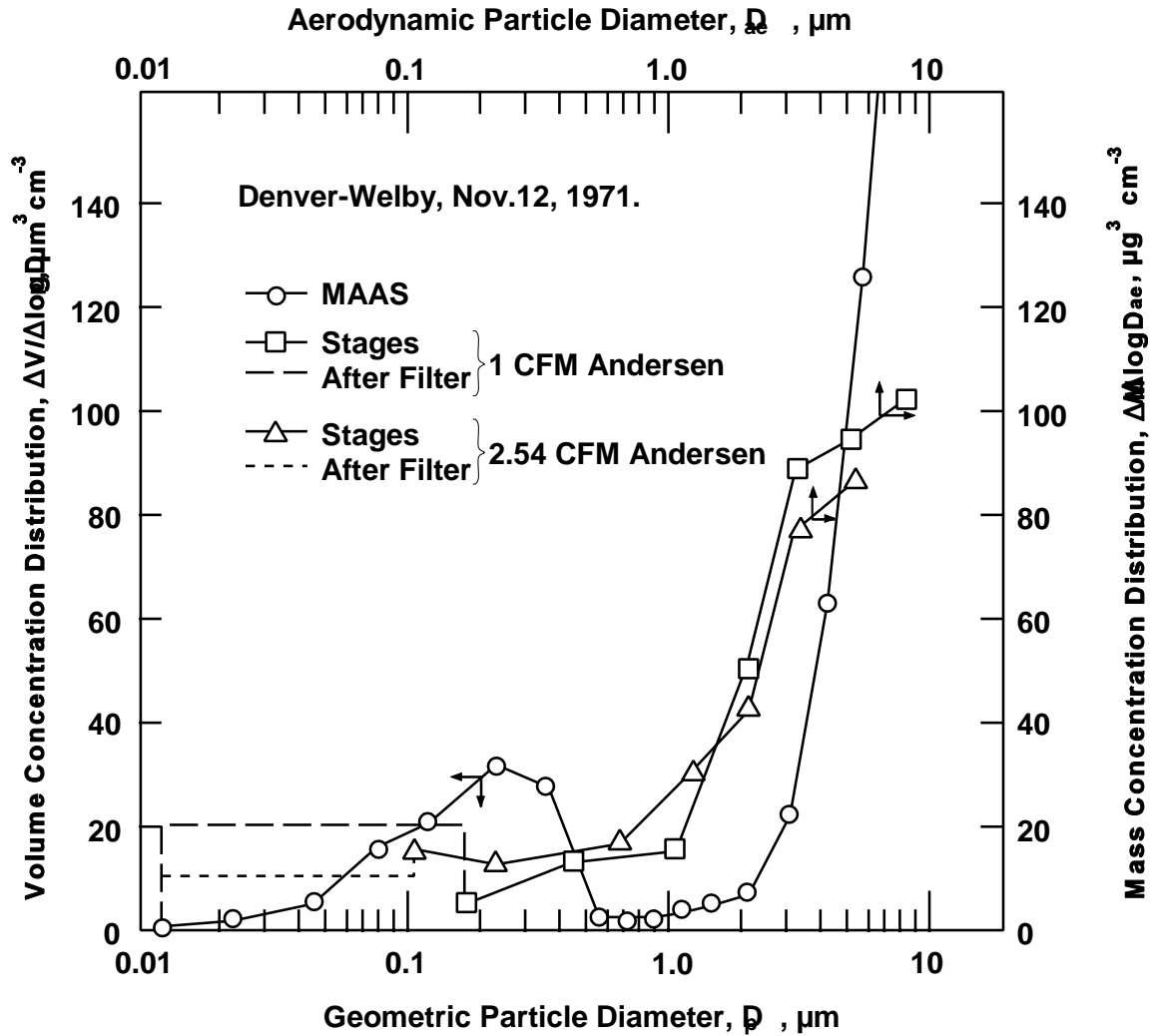


Figure 3-17. These size distributions, obtained during an EPA study of the Denver brown cloud represent one of the few efforts to compare particle-counting and particle-collection size-distribution measurements. Note that impactor data is given in aerodynamic diameter, D_{ae} , and particle-counting data is given in geometric diameter, D_p , derived from the number distribution and estimated density.

Source: Durham et al. (1975).

The "optical" size of a particle depends on the particles shape and refractive index, and on the characteristics of the optical counter. The amount of light scattered by a particle at a wavelength near the particle size varies rapidly with changes in size, wavelength, refractive index, and scattering angle. Therefore, several different optical counters may be needed to cover the range of atmospheric particle sizes. Because of non-linearities in the response of laser or

narrow wavelength optical counters to size changes it is especially difficult to measure particles in the 0.5 to 1.0 size range (Hering and McMurry, 1991; Kim, 1995). Since the amount of scattered light depends strongly on the refractive index it would be useful to calibrate optical counters with particles of the same refractive index as those in the atmosphere. Hering and McMurry (1991) used a differential mobility analyzer to select particles of a uniform geometric diameter. The light scattering of these monodispersed atmospheric particles, as measured by a Particle Measuring System LAS-X optical counter, was compared to that of spheres of polystyrene latex (a substance frequently used to calibrate optical counters) and oleic acid of the same geometric diameter. The atmospheric aerosols scattered less light than polystyrene latex sphere (refractive index = $1.9 - 0.0i$), but about the same amount of light as oleic acid spheres (refractive index = $1.46 - 0.0i$) of the same geometric size. Relating the variety of sizes measured by particle counters and impactors, and displaying them together on an aerodynamic diameter scale, or other scale, is a major task which has not yet been adequately addressed.

The greater width of the coarse modes, as measured by the impactor in Figure 3-17, may be attributed to the use of glass fiber filter paper for the impactor surface. It is now recognized that the use of glass fiber filter material, as contrasted to a flat surface, causes a severe reduction in the effectiveness of the cut. Large particles bounce off the glass fiber (Vanderpool et al., 1987) giving much reduced collection efficiencies; whereas fine particles penetrate into the fiber and some are captured in stages that should have near zero collection efficiencies (Rao and Whitby, 1978). Many studies that used the Anderson High Volume Fractionating Sampler also used glass fiber filters. The use of glass fiber filters as impaction collection surfaces causes any given size range to contain both larger and smaller particles than predicted and thus tends to spread out the modes and fill in the minima. An example of the smoothing effect of glass fiber collection surfaces, and especially the collection of fine particles on upper stages, can be seen in Figure 3-16. Nevertheless, the bimodal nature of the ambient aerosol is still captured.

3.7.5 Review of Size-Distribution Data

3.7.5.1 Early Studies

In 1978, when EPA scientists debated the best cut-point to separate fine particles from coarse particles, there was limited information available. Particle-counting data from California studies had been summarized by Whitby and Sverdrup (1980) and are shown in Figure 3-18. With the exception of one distribution from Pomona, all distributions showed a minimum near 1 μm and indications of significant amounts of coarse particle material between 1.0 and 2.5 μm . (The region between 1 and 2.5 μm will be referred to as the intermodal region.) Other studies of size distribution (McMurry et al., 1981) in the Southeastern United States, provided similar information (Figure 3-19).

Results from several impactor studies were also available, some of which suggested two modes. However, much of the impactor data were considered unreliable in regard to the existence and position of modes (Whitby et al., 1974). However, one of the more extensive and reliable studies available (Patterson and Wagman, 1977) provided confirmation of the Whitby bimodal observations. In this study, mass and composition measurements were made for four different levels of visibility. The histograms for mass, sulfate, and iron for two levels of visibility are shown in Figure 3-20. It is clear that the major portion of the fine mass is below 0.6 μm and the major portion of the coarse mass is greater than 3 μm in diameter. These impactor data, coupled with the more extensive number-size distributions data of Whitby and Sverdrup (1980) led to a preference for a 1 μm cut-point but an acceptance of 2.5 μm on the assumption, then considered to be the case, that 2.5 μm represented the minimum cut-point that was attainable with a dichotomous sampler (Miller et al., 1979).

3.7.5.2 Recent Work

In the intervening 15 years, there has been very little additional work in which particle-counting techniques, covering the entire size range, have been used to measure ambient aerosols. Most of the particle-counting studies have focused on fine and ultrafine particles, diameter <1.0 μm . There have however been a number of impactor studies that provide insight into the size of the fine and coarse modes and into what material is found between them.

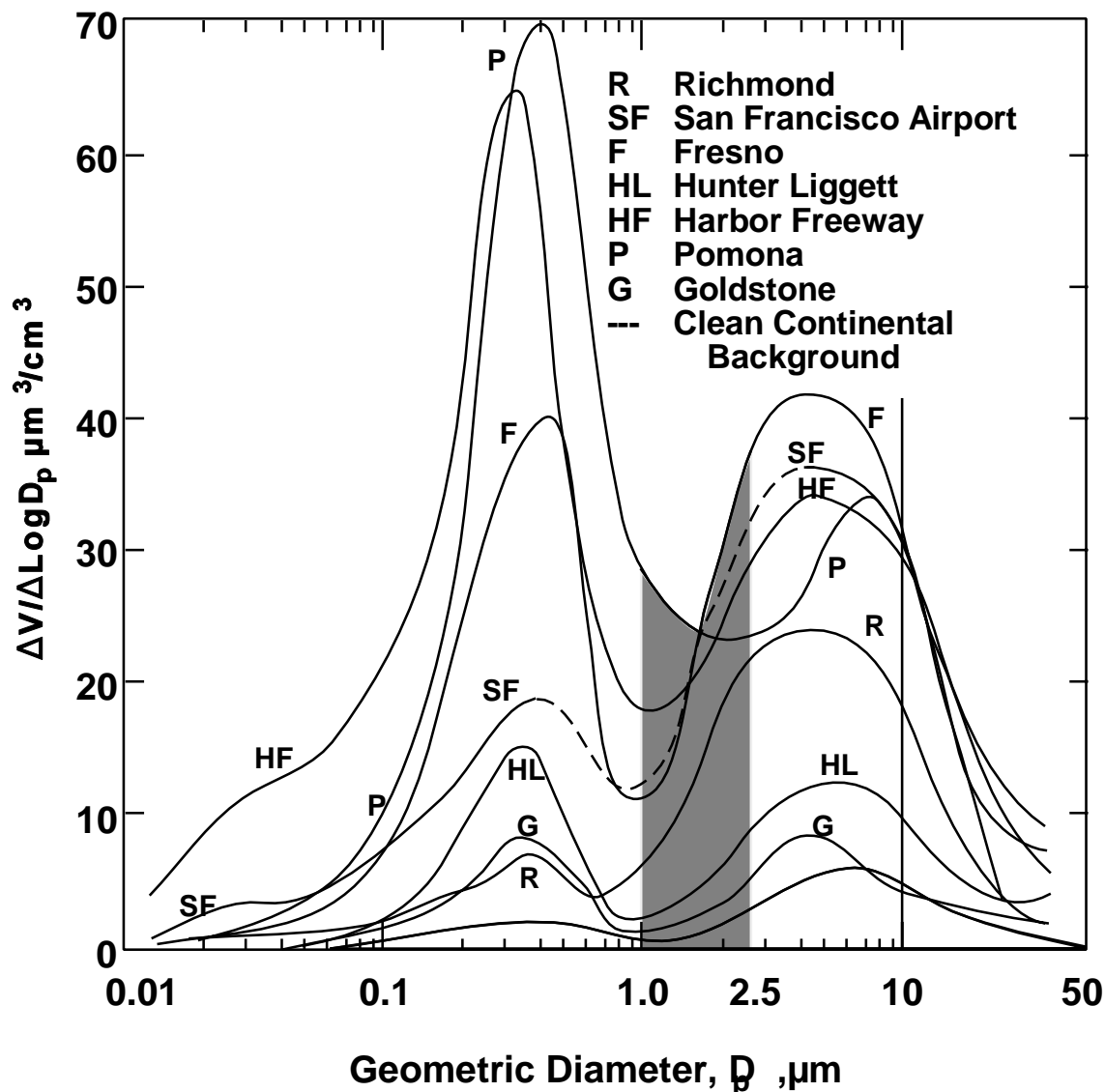


Figure 3-18. Grand average volume-size distributions from the Aerosol Characterization Experiment (ACHEX) in 1972. A size distribution for clean continental aerosol is shown for comparison. Note that with the exception of the Pomona size distribution, all distributions show a distinct minima near 1.0 μm diameter. A line has been added at 1.0 μm , 2.5 μm , and 10 μm diameter to indicate how much of the coarse particle mode is observed between 1.0 and 2.5 μm diameter.

Source: Whitby and Sverdrup (1980).

There are only a few impactor size distribution studies that cover the full size range from 0.01 to 100 μm (Lundgren and Hausknecht, 1982a,b; Lundgren et al., 1984; Burton and Lundgren, 1987; Vanderpool et al., 1987). Lundgren and co-workers used a mobile

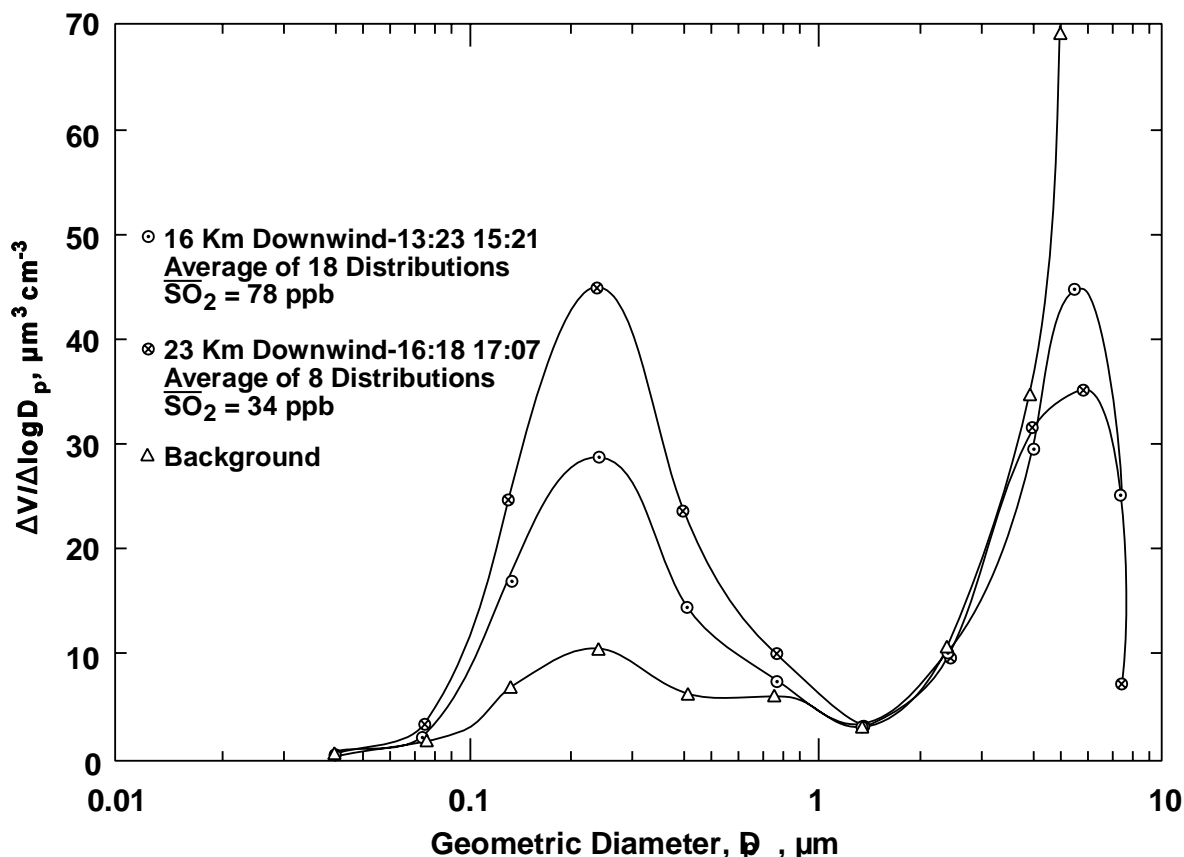


Figure 3-19. Volume-size distribution taken in the midwestern United States near the Cumberland Power Plant in Tennessee. Note that coarse mode decreases and fine mode increased as the mobile sampling van moved downwind farther from urban influence but allowing more time for reaction as the power plant plume mixed with background air and SO_2 was converted to sulfate and NO_x to nitrate.

Source: McMurry et al. (1981).

unit, the wide range aerosol classifier (WRAC), to measure mass-size distribution in ten size ranges from <0.4 to $>50 \mu\text{m}$. Two distributions, averages for Philadelphia and Phoenix, are shown in Figure 3-21. Both clearly indicate a fine particle mode with an MMAD near $0.5 \mu\text{m}$ for Philadelphia and below $0.3 \mu\text{m}$ for Phoenix. Both show a coarse particle mode with an MMAD near $20 \mu\text{m}$ in diameter. However, there is a significant amount of material found in the intermodal region, 1 to $2.5 \mu\text{m}$. Although the intermodal mass is not a significant fraction of the total suspended particulate mass or even of TSP, as would be measured by a high-volume sample (upper cut-point around $25 \mu\text{m}$), it does represent a

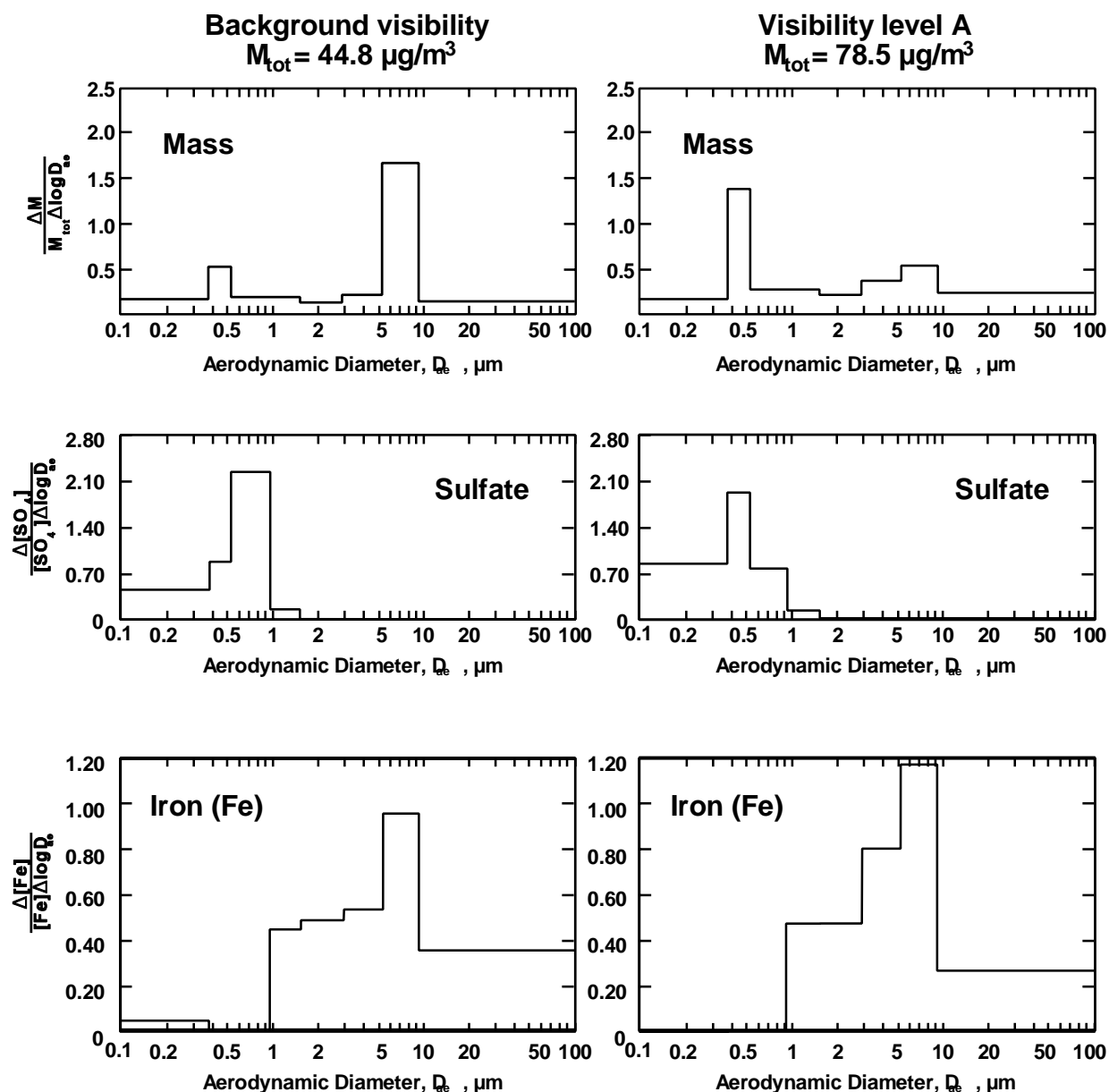


Figure 3-20. Examples of size distribution histograms for total mass, sulfate, and iron obtained at two visibility levels using an Andersen impactor. Arbitrary choice of 0.1 and 100 for lower and upper limits cause the extreme rectangles to be long and low. Note the separation into fine and coarse modes in mass and that sulfate and iron clearly belong in the fine and coarse mode respectively.

Source: Patterson and Wagman (1977).

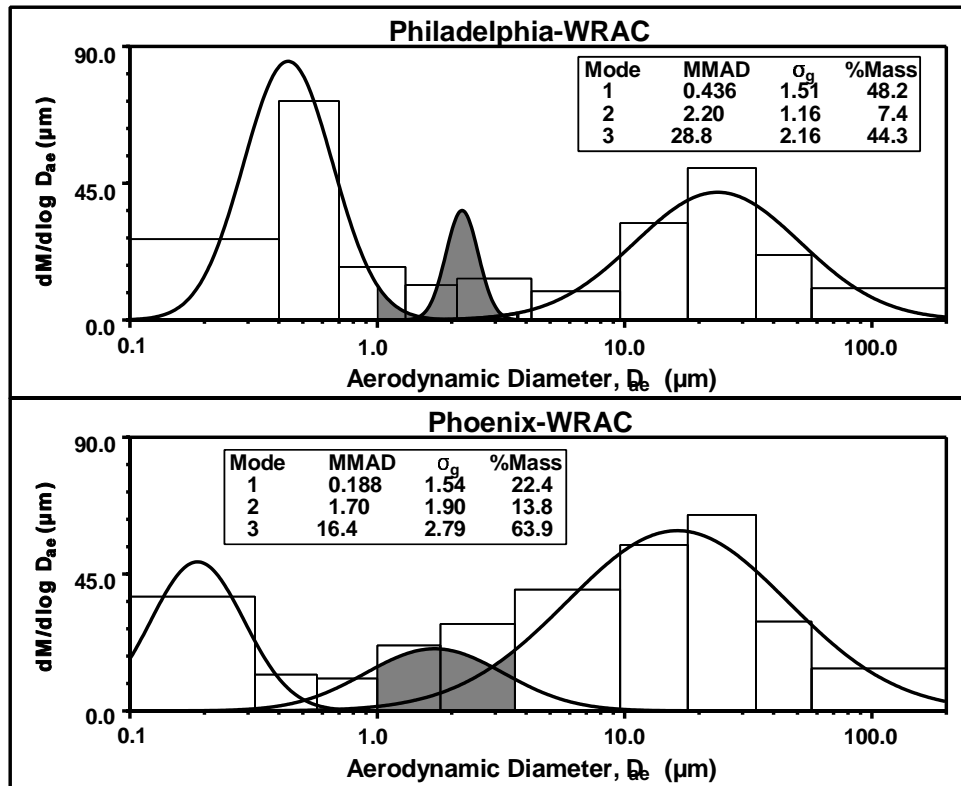


Figure 3-21. Impactor size distribution measurement generated by Lundgren et al. with the Wide Range Aerosol Classifier: (a) Philadelphia and (b) Phoenix. Note the presence of more coarse mode particles in the size range 1 to 2.5 μm , in the dryer environment of Phoenix.

Source: Adapted from Lundgren and Hausknecht, 1982b.

major portion of the coarse fraction of PM_{10} . An attempt has been made to fit the distribution with three, log-normal distributions. In this case, the fit is poor. In the Phoenix case the accumulation mode cannot be defined other than that the MMAD is below 0.2 μm . The coarse particle fractions are very wide suggesting the possibility of two or more modes (Figure 3-24). The material between 1 and 2.5 μm is not a new mode but an indication of either an artifact due to particle bounce, or a long-lasting tail of the coarse distribution.

The existing size-distribution data were recently reviewed by Lundgren and Burton (1995), with emphasis on the coarse mode. They concluded that the coarse mode could be reasonably well described by a lognormal distribution with a mass median aerodynamic diameter (MMAD) of 15 to 25 μm and a mode spread (σ_g) of approximately two. This allows one to calculate, for a freshly-generated coarse mode aerosol, that about 1% of the

mass would be less than $2.5\ \mu\text{m}$ and only about 0.1% would be less than $1.0\ \mu\text{m}$ in diameter. This conclusion is confirmed by data from Whitby in which a wind change allowed a measurement of fresh coarse mode aerosol (National Research Council, 1979). As can be seen in Figure 3-22, the intermodal mass, 1.0 to $2.5\ \mu\text{m}$, was not affected, even though the mass at $20\ \mu\text{m}$ increased substantially.

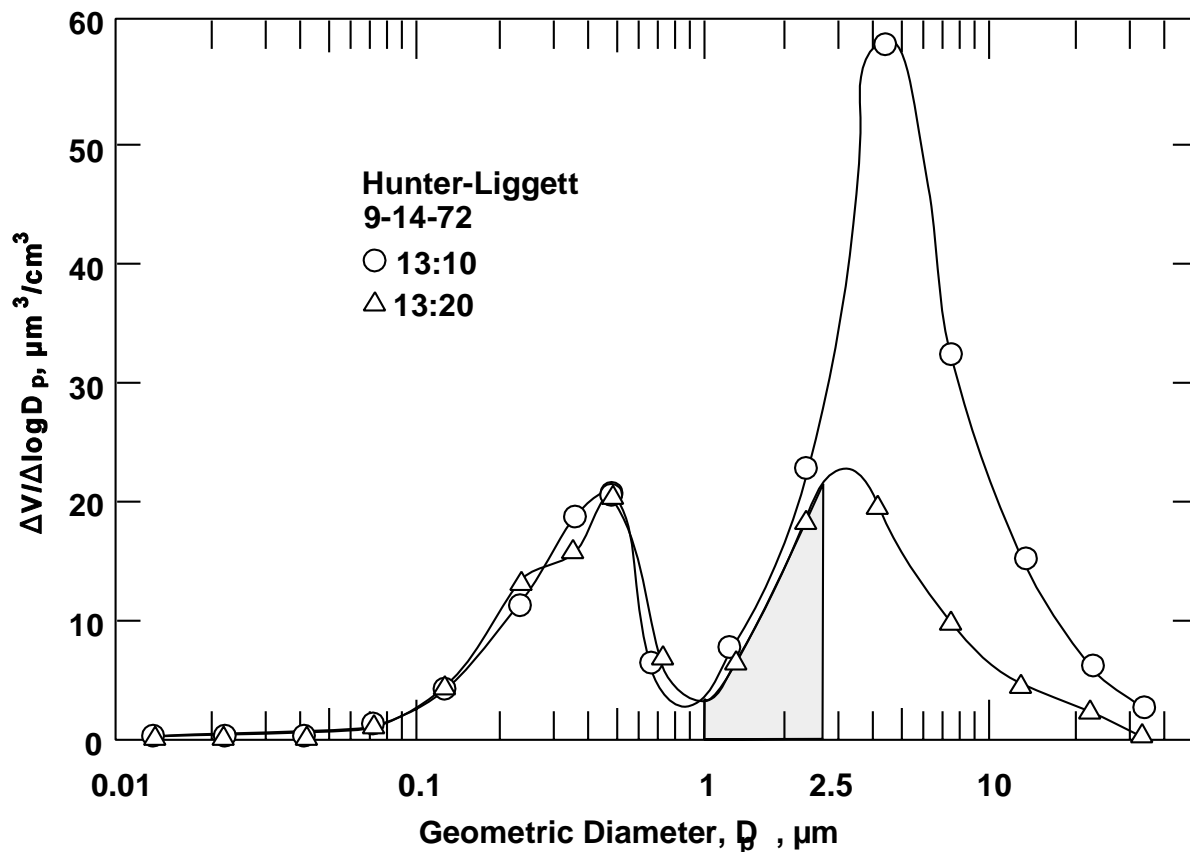


Figure 3-22. Example of aged and fresh coarse mode particle size distributions. A sudden wind change brought fresh wind-blown dust to the sampler, operated as part of the South Coast Air Quality Study. Note that there is only a very small change in the intermodal mass, 1.0 to $2.5\ \mu\text{m}$ diameter, although there is a major increase in the mass between 2.5 and $10\ \mu\text{m}$ in diameter.

Source: National Research Council (1979).

Another extensive set of studies covering the full size range, but limited to the Chicago area, has been reported by Noll and coworkers (Lin et al., 1993, 1994). They used an Andersen impactor for smaller particles and a Noll Rotary Impactor for larger particles. Results of Lin et al. also indicate a bimodal mass distribution. For the shorter time interval measurements (8 or 16 h), the average MMAD for the fine mode was $0.42\ \mu\text{m}$, with a σ_g around two. The average MMAD of the coarse mode was $26\pm 8\ \mu\text{m}$, with a σ_g varying from 2.0 to 3.5. As shown in Figure 3-23, the results of Noll and coworkers (Lin et al., 1993, 1994) also suggest that in some instances little coarse mode material is found in the intermodal region, 1.0 to $2.5\ \mu\text{m}$. Lin et al. (1993) combined material on the 0.65 to $1.0\ \mu\text{m}$ and the 1.0 to $2.0\ \mu\text{m}$ stages before weighing. Therefore, the MMAD of the accumulation mode is not as well defined as it might be, and could be smaller than that given by the fitting process. Therefore, these results cannot be used to show that some fine PM is found above $1.0\ \mu\text{m}$. When fitted to two log-normal distributions the fit is poor and the coarse mode is very wide. The fit with three log-normal distributions is used to show the possibility of particle bounce or a second mode within the coarse particle size range contributing to mass in the intermodal ($1\text{--}2.5\ \mu\text{m}$) region.

3.7.6 Intermodal Region

3.7.6.1 Coarse Mode

The question then arises, what portion of the coarse mode material found in the intermodal region is real and what portion is artifact? As discussed in Section 3.3.3.2.4, the optical size may differ from the geometric or aerodynamic size. Optical counters are normally calibrated with latex particles, or other particles of a specific refractive index. Atmospheric particles with different refractive indices would be incorrectly sized if the difference in refractive index resulted in a difference in the amount of light scattered by the particles (Wilson et al., 1988; Liu et al., 1992; Hering and McMurry, 1991). For particle counters using lasers, particles of different sizes within the 0.5 to $1.0\ \mu\text{m}$ range may give the same light scattering (Hering and McMurry, 1991; Kim 1995).

In the case of impactors, it is possible that an artifact may arise from particle bounce, from fragmentation of larger agglomerates, or from loosening of material from other surfaces by impacting particles. The problem of particle bounce in impactors has been treated

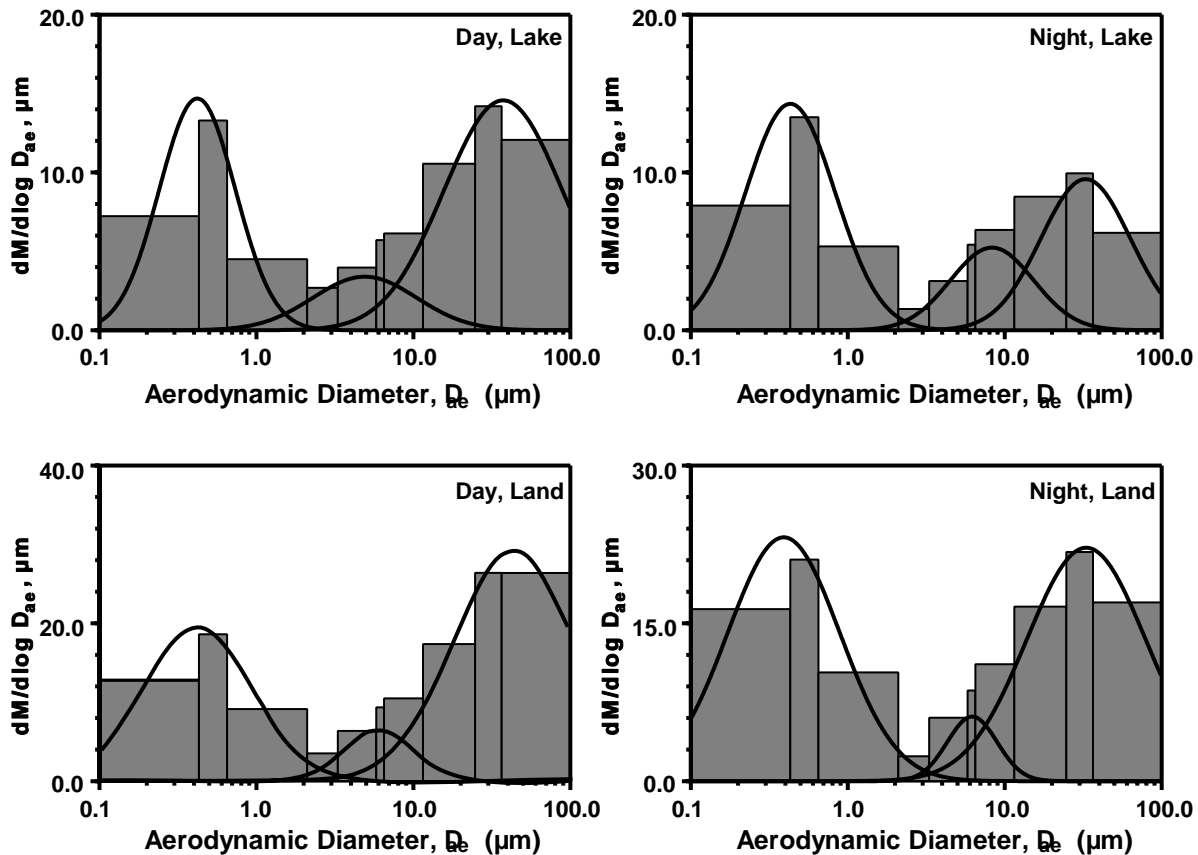


Figure 3-23. Size distributions reported by Noll and co-workers from the Chicago area using an Anderson impactor for the smaller particles and a Noll Rotary Impactor for the larger particles.

Source: Lin et al. (1993).

theoretically and practically in many studies (Wang and John, 1987, 1988). Most workers coat the coarse particle stages with a grease or oil to reduce bounce. However, as the surface becomes covered with aerosols, a particle may impact another particle instead of the surface and either bounce to a lower stage or cause deagglomeration and reentrainment of previously collected particles (John et al., 1991; John and Sethi, 1993). As impactor collection plates become loaded or as inlet upper size cut surfaces become dirty, the magnitude of the effect increases (Ranade et al., 1990; John and Wang, 1991). One result is a lowering of the effective cut point of the inlet and the impactor stages. Thus, it is uncertain how much of the mass found in the intermodal size range is real and how much is due to artifacts.

There are several reasons to believe, however, that some of the intermodal mass may be real. For example, Lundgren and Burton (1995) point out that the lifetime of particles in the atmosphere is a strong function of their aerodynamic size. Thus, while freshly generated coarse mode aerosol may have a MMAD of $20\text{ }\mu\text{m}$, with only 1% below $2.5\text{ }\mu\text{m}$, as the aerosol ages the larger particles will rapidly fall out, leaving a distribution enriched with particles in the small-size tail of the distribution.

A second explanation has to do with the possible multimodal nature of dust generated by wind or vehicular traffic. A study by the U.S. Army (Pinnick et al., 1985) measured the size distribution of dust generated by heavy vehicles driven on unpaved roadways in the arid southwestern United States. A variety of light-scattering instruments were used and were recalibrated for the refractive index of the soil particles. The occurrence of strong surface winds (gusts of $15\text{ to }20\text{ m s}^{-1}$) during the study permitted, in addition to the vehicular-generated dust, some measurements of windblown dust. There were some differences between sandy soil and silty soil, and between dust generated by vehicular traffic and by wind. However, all situations produced a bimodal size distributions. The upper mode had an MMAD that ranged from 35 to $53\text{ }\mu\text{m}$, with σ_g from 1.37 to 1.68. Of particular interest, however, was a second mode having an MMAD that varied from 6.2 to $9.6\text{ }\mu\text{m}$, with a σ_g from 1.95 to 2.20. (One measurement in silty soil had an MMAD of $19.4\text{ }\mu\text{m}$.) The MMADs of the smaller coarse particle modes are significantly smaller than those coarse mode MMADs observed by Lundgren or Noll. An example of vehicular generated dust is shown in Figure 3-24. Note that the differential mass is plotted on a logarithmic scale. These results suggest that in arid areas, significant soil material, generated by traffic or wind, may be found in the intermodal region.

A third reason for believing that the intermodal mass is real has to do with the relative size efficiency of particle removal equipment used on power plants and other large industrial facilities. Older control devices, which may still be used in some applications, allow significant particle mass to escape. Overall mass efficiencies are approximately 80% for cyclones and 94% for scrubbers. Modern control devices have very high overall efficiencies, 99.2% for electrostatic precipitators (ESP) and 99.8% for baghouses. However, all of these devices have efficiencies for coarse particles that decrease with decreasing size. Efficiencies typically reach a minimum between $0.1\text{ and }1\text{ }\mu\text{m}$ and increase for particles

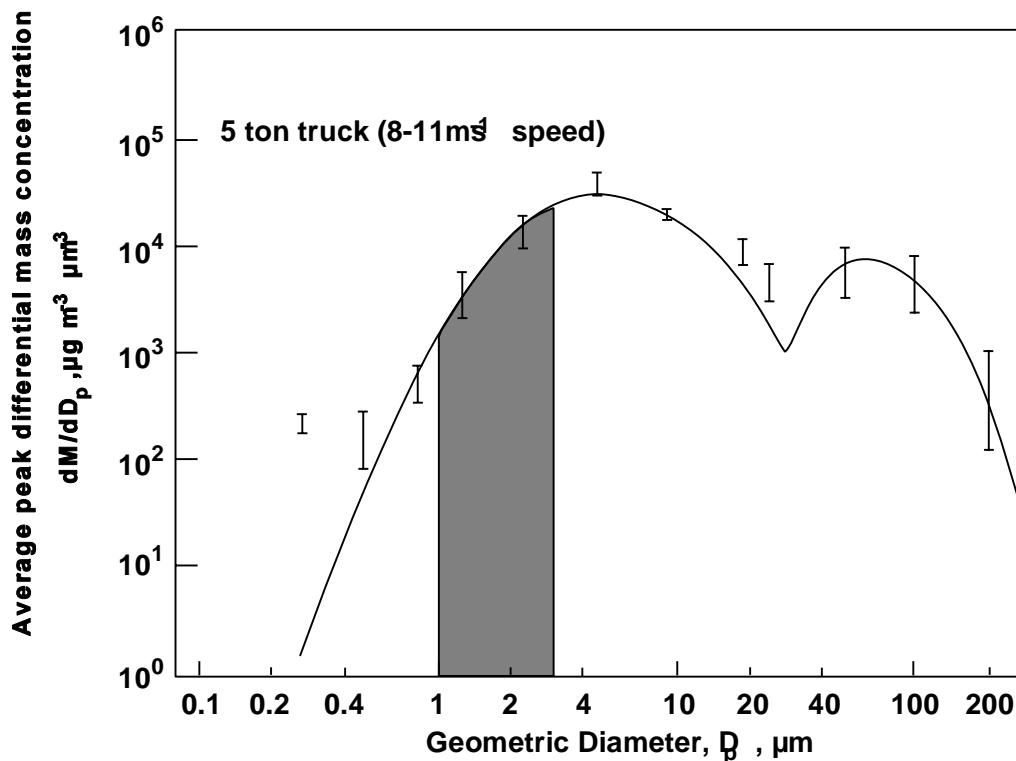


Figure 3-24. Size distribution of dust generated by driving a truck over an unpaved test track. "Error bars" show the range of distributions from individual tests. The curves shown are log-normal fits to the average distribution. The original data were plotted as log radius but have been replotted versus log diameter. The shaded bar between lines at diameters of 1.0 and 2.5 μm indicates how the smaller size mode of this dust can contribute to the intermodal mass found in arid areas (see Figures 3-21 and 3-23).

Source: Pinnick et al. (1985).

smaller than 0.1 μm . Thus, although most of the particulate mass is captured, the particles that do escape are in the smaller size range. Data from U.S. EPA, plotted in Figure 3-25, (U.S. Environmental Protection Agency, 1995) show the size distribution of fly ash from a pulverized coal power plant and the size distribution of the material escaping from the various control devices. The small-size tail of the coarse mode escapes preferentially and may possibly contribute material to the intermodal region.

Cheng et al. (1985) reported experimental measurements from an atmospheric fluidized-bed coal combustor. Size distribution measurements, made downstream of a cyclone and again downstream from baghouse filtration of the material leaving the cyclone, are shown in

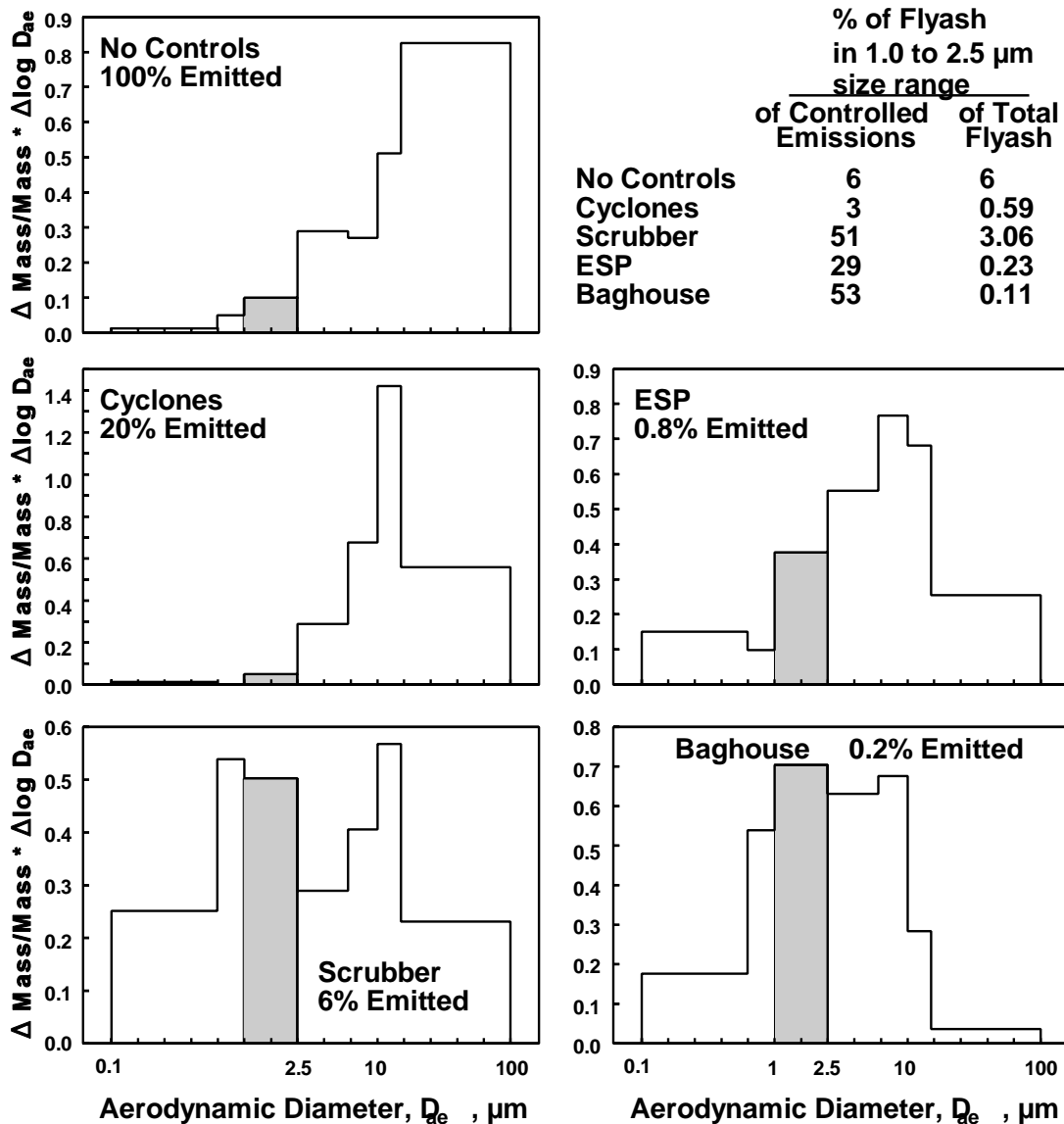


Figure 3-25. Size distribution of emissions from a pulverized-coal power plant and the particle size distributions remaining after several types of control devices.

Source: U.S. Environmental Protection Agency (1995).

Figure 3-26 (Cheng et al., 1985). Electron microscope photographs confirmed a fine particle mode of spherical particles between 0.1 and 0.25 μm , presumably formed from evaporation and condensation of volatile species from the coal matrix; and irregular-shaped chunks from the coarse mode with a peak concentration between 1 and 3 μm in diameter.

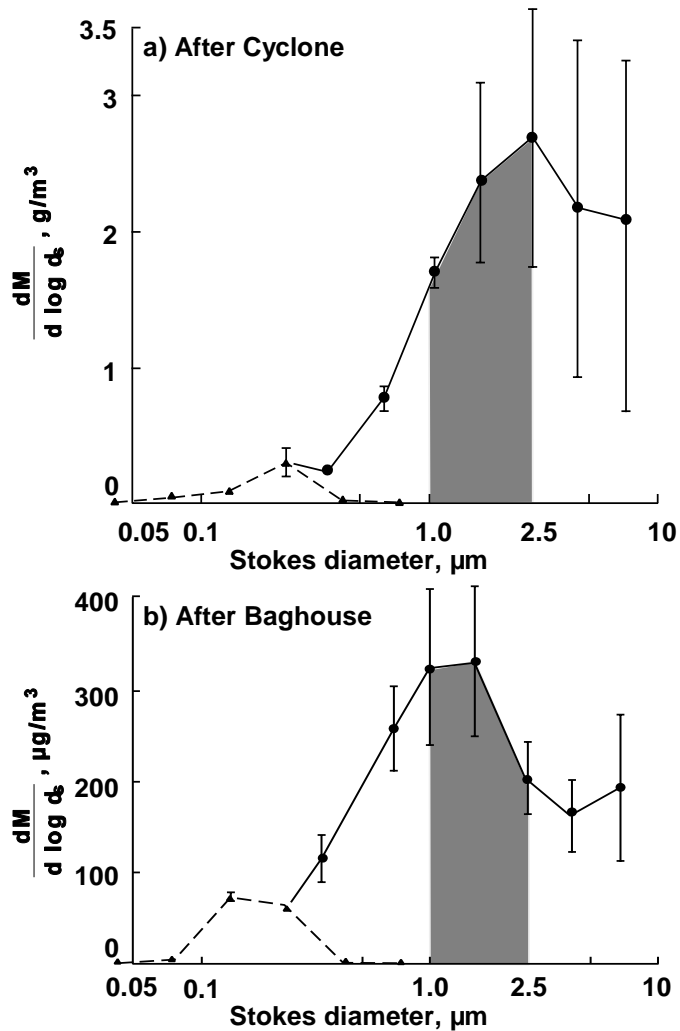


Figure 3-26. Size distributions from a fluidized-bed, pulverized coal combustor, (a) after initial cleanup by a cyclone collector and (b) after final cleanup by a baghouse.

Source: Cheng et al. (1985).

A fourth piece of evidence comes from studies in which measurements are made of the elemental composition of $\text{PM}_{2.5}$ and PM_{10} or the coarse fraction of PM_{10} . Elements representative of soil type material have been found in the $\text{PM}_{2.5}$ fraction. In a study in Philadelphia that used dichotomous samplers, an amount of soil-type material equal to 5% of the coarse mode fraction of PM_{10} was found in the $\text{PM}_{2.5}$ fraction (Dzubay et al., 1988). Since the virtual impactor used in the dichotomous sampler minimizes particle bounce and reintrainment, this would appear to be the small-size tail of the coarse mode in the 1 to 2.5 μm size range.

Similar results have been reported from the IMPROVE network (Eldred et al., 1994).

Elemental analysis suggested that soil-derived material, equal to 20% of the coarse fraction of the PM_{10} sample, was found in the $PM_{2.5}$ sample.

Thus, one can conclude that coarse mode material is found in the intermodal region. There are reasons to suspect that a portion of this material is an artifact but that a portion is real coarse mode material having an aerodynamic diameter between 1.0 and 2.5 μm . In either event, this can lead to a misunderstanding of the source of the particles, to inappropriate control strategies, or to exposure studies that fail to differentiate correctly between fine and coarse particles.

3.7.6.2 Fine Mode

This section discusses the source of fine mode material found in the intermodal region. Early particle-counting data suggested that, with a few exceptions, significant mass of fine mode material would not be found above 1 μm (see Figures 3-13, 3-18, 3-19, and 3-20). However, impactor studies, on some occasions, have observed significant mass on stages with a cut point of 1 μm . In some instances, the MMAD of the fine mode was as large as 1 μm (John et al., 1990). The change in relative humidity produced by a few degrees change in temperature can significantly modify the MMAD of an ambient aerosol size distribution. As the RH approaches 100%, accumulation mode aerosols, with dry sizes below 1.0 μm in diameter, may grow larger than 2.5 μm in diameter, be rejected by $PM_{2.5}$ samples, and be counted as coarse particles.

Before examining additional field data demonstrating the effect of relative humidity on particle size, it is useful to review some basic information on the interaction of water vapor with the components of fine particles. Sulfuric acid (H_2SO_4) is a hygroscopic substance. When exposed to water vapor a H_2SO_4 droplet will absorb water vapor and grow in size until an equilibrium exists between the liquid water concentration in the H_2SO_4 solution droplet and the water vapor concentration in the air. The amount of water in the sulfuric acid droplet will increase and decrease smoothly as the RH increases and decreases. Ammonium sulfate, $(NH_4)_2SO_4$, however, is deliquescent. If initially a crystal in dry air, it will remain a crystal until a certain RH is reached; at this point it will absorb water and become a solution droplet. The RH at which this happens, $\approx 80\%$ RH in the case of

$\text{NH}_4)_2\text{SO}_4$, is called the deliquescent point. At RH's above the deliquescent point the $(\text{NH}_4)_2\text{SO}_4$ droplets are hygroscopic, gaining or losing water reversibly as the RH increases or decreases. If the RH decreases below the deliquescent point the solution droplet becomes supersaturated and unstable to crystallization. However, sub-micron sized droplets will remain supersaturated until a significantly lower RH, known as the crystallization or efflorescent point is reached. The crystallization point decreases with decreasing droplet size and decreasing purity (Whitby, 1984). Thus, for a deliquescent substance, a plot of droplet diameter or water content as a function of RH will have two lines, one for increasing RH and another for decreasing RH. An example of this phenomenon, known as hysteresis, is shown in Figure 3-27. Table 3-16 shows the RH at the deliquescent and crystallization points for some compounds found in the atmosphere.

Much experimental and theoretical effort has gone into understanding this process. The basic theory was elucidated by Hänel (1976). Much experimental work has been done on atmospheric species (e.g., Tang and Munkelwitz, 1977, 1993; Richardson and Spann, 1984). The electrodynamic balance, by which single particles can be studied, has advanced the understanding of particle-water vapor equilibrium, especially for particles in metastable states, e.g., the supersaturated solution particles which are responsible for the hysteresis loop shown in Figure 3-27 (Cohen et al., 1987a,b; Chan et al., 1992; Kim et al., 1994). Ammonium nitrate, NH_4NO_3 , because of its volatility, is difficult to handle but has been studied successfully by Richardson and Hightower (1987). The aerosol equilibria models developed by Seinfeld and co-workers allow calculation of the water content of bulk solution as a function of relative humidity (Kim and Seinfeld). The model SCAPE (Kim et al., 1993a,b) has been used to estimate the contribution of water to suspended aerosol mass in the California South Coast Air Basin using particle composition data from the 1987 Southern California Air Quality Study (Meng et al., 1995). From midnight to early morning, when the temperature is low and relative humidity is high, water was usually the predominant aerosol substance. Particulate water in the winter was estimated to be considerably larger than in the summer at each of the four sites studied.

The water content of a sub-micron sized droplet, and therefore its size, depends not only on the dry size but is a result of a balance between surface tension and solute concentration (Li et al., 1992). Pure water is in equilibrium with its vapor when the RH

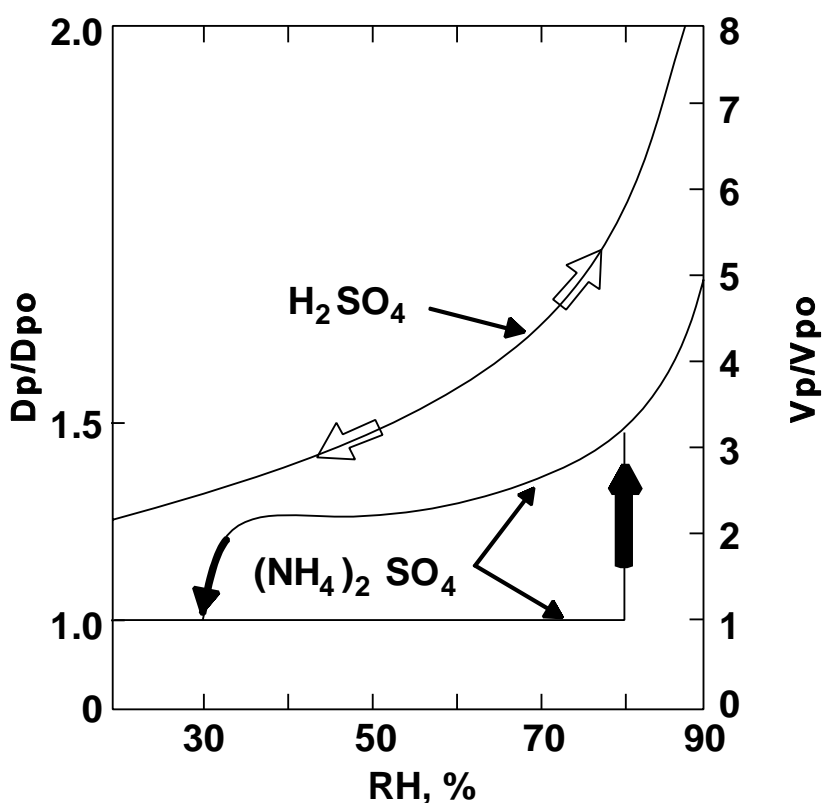


Figure 3-27. Particle growth curves showing fully reversible hygroscopic growth of sulfuric acid (H₂SO₄) particles, deliquescent growth of ammonium sulfate [(NH₄)₂SO₄] particles at about 80% relative humidity (RH), hygroscopic growth of ammonium sulfate solution droplets at RH greater than 80%, and hysteresis (the droplet remains supersaturated as the RH decreases below 80%) until the crystallization point is reached.

Source: National Research Council (1993) adapted from Tang (1980).

TABLE 3-16. RELATIVE HUMIDITY OF DELIQUESCENCE AND CRYSTALLIZATION FOR SEVERAL ATMOSPHERIC SALTS^a

Compound	Deliquescence	Crystallization ^c
(NH ₄) ₂ SO ₄	79.9 ± 0.5	37 ± 2
NH ₄ HSO ₄	39.0 ± 0.5 ^b	
NH ₄ NO ₃	61.8	
NaCl	75.3 ± 0.1	42

^aTaken from Tang and Munkelwitz (1993) unless otherwise indicated.

^bTang and Munkelwitz (1977).

^cShaw and Rood (1990) and references therein.

equals 100% and is therefore, stable, i.e. the rate of evaporation equals the rate of condensation. The water in a solution will be in equilibrium with water vapor at a lower water vapor concentration because the presence of solute molecules or ions lower the rate of evaporation. Therefore, a solution will absorb water and become more dilute, increasing the water vapor concentration needed for equilibrium until the solution water vapor concentration required for equilibrium matches the ambient water vapor concentration or RH. As the droplet size decreases the surface tension increases and the vapor pressure of water required to maintain equilibrium increases. Therefore, the smaller the dry size of the particle, the less the amount of growth as RH increases.

Theoretical calculations of the growth of various sizes of ammonium sulfate particles and an experimental verification of such calculations, using a simulation of the humidification process in the human lung, are shown in Figure 3-28. Note the very rapid increase in the amount of water and in the diameter of the aerosol particle as the relative humidity approaches 100% RH. Considering the difficulty of measuring relative humidity accurately between 99 and 100%, theory and experiment are in reasonable agreement. As can be seen the effect of surface tension is most important for particles with dry size less than 100 nm ($0.1\ \mu\text{m}$). This phenomenon may be of importance in considering the biological effect of water-soluble pollutants. Accumulation mode particles will be diluted when exposed to humidification in the lungs. Ultrafine or nuclei mode particles will not be diluted as much. In the atmospheric aerosol the number distribution will almost always be dominated by particles below 100 nm (see Section 3.1.2). However, aerosols generated in the laboratory for exposure studies probably lack the smaller particles found in the atmosphere. This provides a hypothesis for the difference in effects observed in epidemiological studies and laboratory exposure studies. The importance of this more concentrated, ultrafine droplet component of the atmospheric aerosol may have been neglected because most of the experimental studies of hygroscopicity have used near-micron-sized particles. However, in the modeling of deposition of hygroscopic particles, workers, such as Martonen (1993), have corrected the experimental curves of particle size as a function of RH, based on measurements of near micron-sized particles, to account for the effects of surface tension on ultrafine particles.

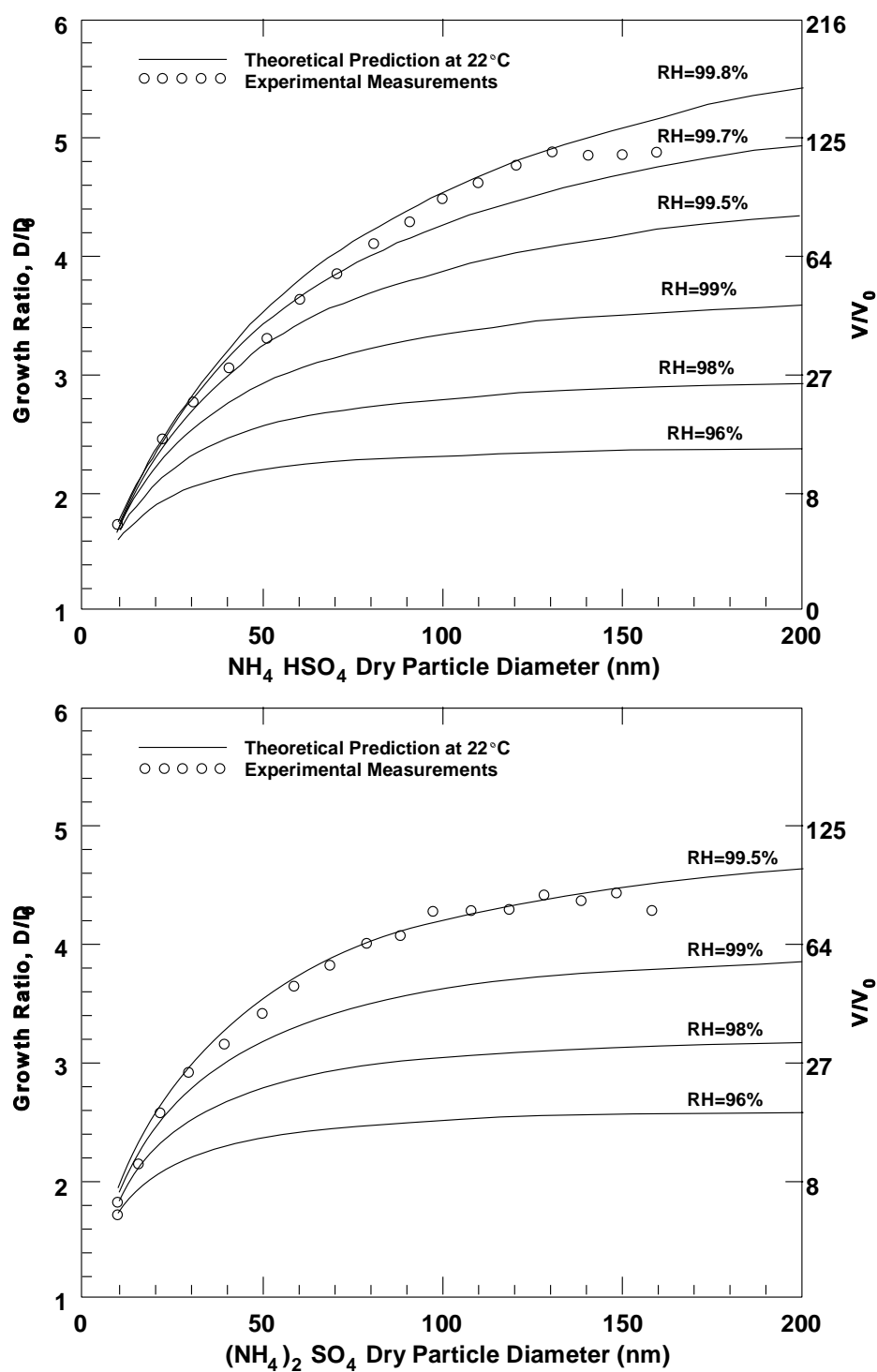


Figure 3-28. Theoretical predictions and experimental measurements of growth of NH_4HSO_4 and $(\text{NH}_4)_2\text{SO}_4$ particles at relative humidity between 95 and 100%.

Source: Li et al. (1992).

In addition to the laboratory studies discussed above there are some measurements on the effect of RH changes on atmospheric aerosol. McMurry and co-workers have made use of a Tandem Differential Mobility Analyzer (TDMA) system (Rader and McMurry, 1986) to measure the change in particle size with changes in relative humidity at Claremont, CA, as part of the Southern California Air Quality Study (SCAQS) (McMurry and Stolzenberg, 1989) and at the Grand Canyon National Park, AZ, as part of the Navajo Generating Station Visibility Study (Zhang et al., 1993; Pitchford and McMurry, 1994). One mobility analyzer is used to isolate a narrow size distribution. After humidification the size distribution of this fraction is measured. An example is shown in Figure 3-29. Note that Figure 3-29 is a number size distribution not a mass size distribution. Particle growth with increasing RH is evident. However, between 70 and 91% RH the distribution splits into less-hygroscopic and more-hygroscopic components. Pitchford and McMurry (1994) attribute this splitting to external mixing, i.e. there are two relatively distinct classes of particles, both containing some soluble and some non-soluble material, with the more hygroscopic component containing significantly more soluble and hygroscopic material. A summary of the results of these studies is given in Table 3-17 (Zhang et al., 1993). The difference in growth rates may be due both to size and to variation in composition as a function of size. The lower growth factor for 0.2 μm particles in Claremont relative to the Grand Canyon may be due to a higher concentration of non-soluble organic material in Claremont.

While there is a significant amount of information on the hygroscopic properties of inorganic compounds, much less is known about the hygroscopic properties of organic components of the atmospheric aerosol. Saxena et al. (1995) have examined the hygroscopic properties of several organic species and noted that water soluble organics may be hygroscopic or deliquescent. Using concurrent cascade impactor samples, they determined the composition of the Grand Canyon and Claremont aerosol, whose size distribution as a function of relative humidity was discussed above. They compared the observed water content at the higher relative humidity with the water content calculated for the inorganic components. They concluded "that the aggregate hygroscopic properties of inorganic particles are altered when organics are also present. Furthermore, the alterations can be positive or negative. The findings are consistent with the expectation that organics are

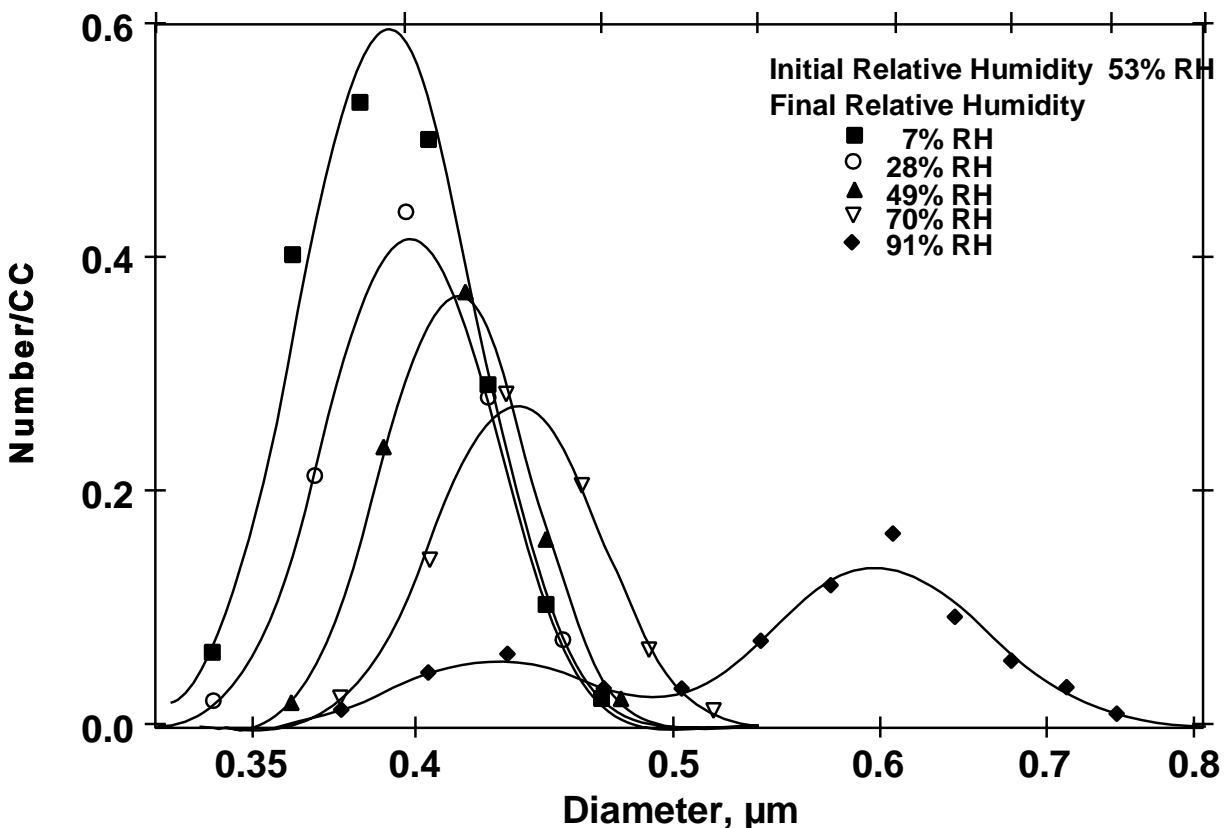


Figure 3-29. Tandem Differential Mobility Analyzer measurements of the sensitivity of particle size to relative humidity at Claremont, CA. Particle number concentrations varied during the measurement, therefore changes in relative size with humidity are meaningful but changes in number concentration are not.

Source: McMurry and Stolzenberg (1989).

predominantly secondary (and thus likely to be hydrophilic) in nonurban areas and predominantly primary (and hence hydrophobic) in urban areas".

Some experimental examples of the significant effect of relative humidity on ambient aerosol size distributions are shown in Figure 3-30 (Lowenthal et al., 1995). In this work, impactor collection and ion chromatographic analysis were used to measure sulfate size distributions over short enough periods to demonstrate the effects of changing relative humidities. The results suggest that the lognormal distribution is preserved as relative humidity increases, but that the MMAD increases. This effect is especially pronounced as the relative humidity approaches 100%.

TABLE 3-17. SUMMARY OF HYGROSCOPIC GROWTH FACTORS^a

1987 SCAQS, Claremont, CA		
Dry Size (μm)	More Hygroscopic Peak $\frac{D_p(90 \pm 3\% \text{ RH})}{D_p(0\% \text{ RH})}$	Less Hygroscopic Peak $\frac{D_p(87 \pm 2\% \text{ RH})}{D_p(0\% \text{ RH})}$
0.05	1.14 ± 0.05	1.03 ± 0.03
0.2	1.23 ± 0.08	1.02 ± 0.02
0.4	1.63 ± 0.11	1.04 ± 0.05
0.5	1.59 ± 0.08	1.07 ± 0.03
1990 NGS Visibility Study, Grand Canyon, AZ		
Dry Size (μm)	More Hygroscopic Peak $\frac{D_p(89 \pm 4\% \text{ RH})}{D_p(0\% \text{ RH})}$	Less Hygroscopic Peak $\frac{D_p(89 \pm 4\% \text{ RH})}{D_p(0\% \text{ RH})}$
0.05	1.36 ± 0.08	1.14 ± 0.10
0.10	1.42 ± 0.08	1.17 ± 0.09
0.20	1.49 ± 0.11	1.17 ± 0.10
0.30	1.51 ± 0.09	1.14 ± 0.10
0.40	1.43 ± 0.10	1.07 ± 0.03

^aValues are mean \pm standard deviations.

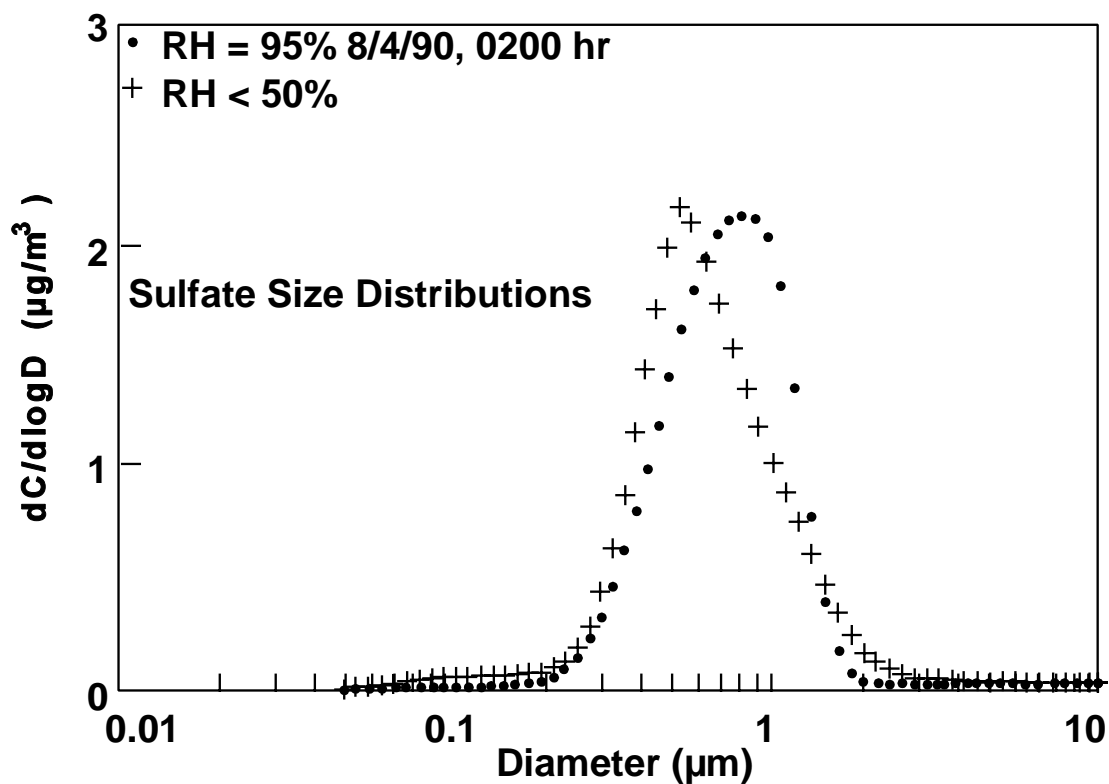
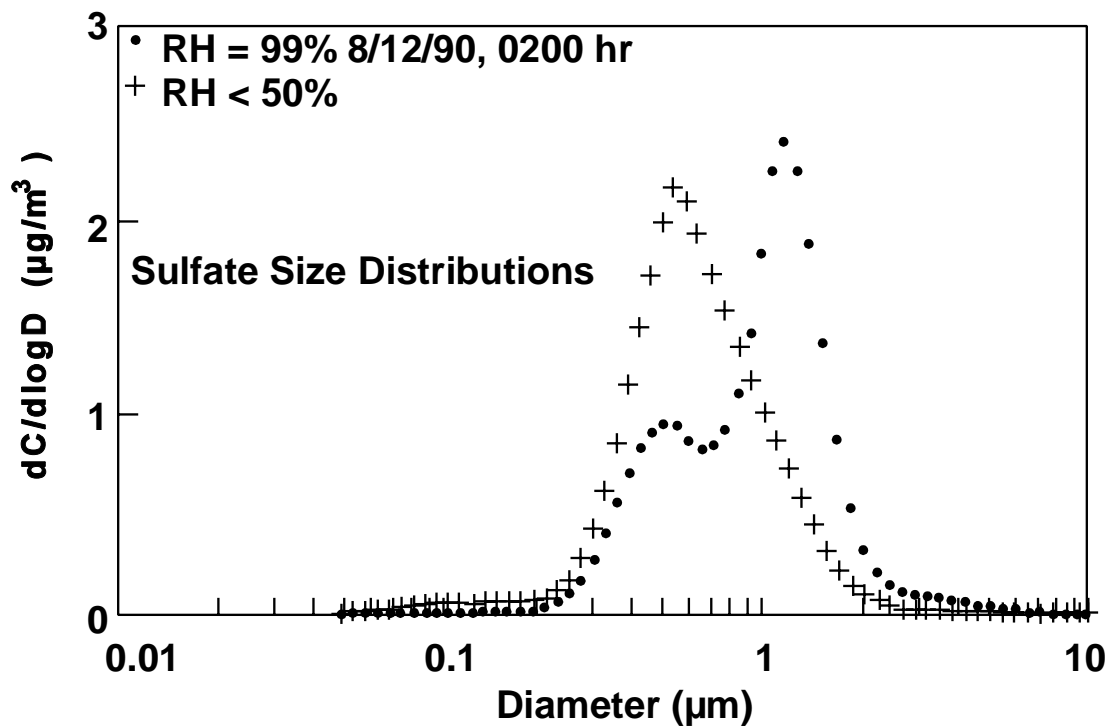


Figure 3-30. Example of growth in particle size due primarily to increases in relative humidity from Uniontown, PA.

Source: Lowenthal et al. (1995).

There are also studies of the behavior of ambient aerosols as the relative humidity is reduced by heating the sampled air. Shaw and Rood (1990) report a study using a heated integrating nephelometer in which crystallization RHs of 4 to 67% were observed. Similar studies in Washington, D.C. by Fitzgerald et al. (1982) found no evidence of crystallization or efflorescence when RH was reduced to 30% RH.

Further experimental evidence of the effect of decreasing relative humidity on aerosol size distribution is provided by impactor data reported by Berner (1989) and is shown in Figure 3-31. One impactor sampled aerosol in its humidified state directly from the atmosphere. The inlet of a second impactor was warmed $\approx 7^\circ\text{C}$ above the ambient temperature of $\approx 5^\circ\text{C}$ in order to evaporate most of the particle-bound water before collecting the aerosol. The water and other volatile material in both the "wet" and the "dry" samples would evaporate in the laboratory prior to weighing the impactor stages. As can be seen, in the ambient air most of the non-volatile mass was above $1.0\ \mu\text{m}$ with significant amounts above $2.5\ \mu\text{m}$. However, after heating the size of the aerosol was reduced so that most of the non-volatile mass was below $1.0\ \mu\text{m}$. Berner treated the distributions as monomodal and derived growth factors of 4.9 for fog and 4.1 for haze. If the observations are treated as multimodal, good bimodal, or as shown in Figure 3-31, trimodal fits are obtained. This splitting into "more" and "less" hygroscopic modes at high relative humidity has been observed by McMurry and co-workers (McMurry and Stolzenberg, 1989; Zhang et al., 1993) (Figure 3-29) and Lowenthal et al. (1995) (Figure 3-30). In some cases, reported by Pitchford and McMurry (1994), splitting into three modes of varying hygroscopicity was observed. However, the separation into two "more" hygroscopic modes may represent, as suggested by Berner, variations in relative humidity extremes during different parts of the overnight sampling period.

In measuring light scattering with the integrating nephelometer, the aerosol community has been very concerned about the difference in relative humidity and temperature in the ambient air and in the volume of air in which particle scattering is actually measured (Covert et al., 1972; Fitzgerald et al., 1982). Temperature differences between the measurement volume and ambient air of 1 or 2°C can change the relative humidity and change the observed light scattering. Great efforts have been made to minimize this temperature

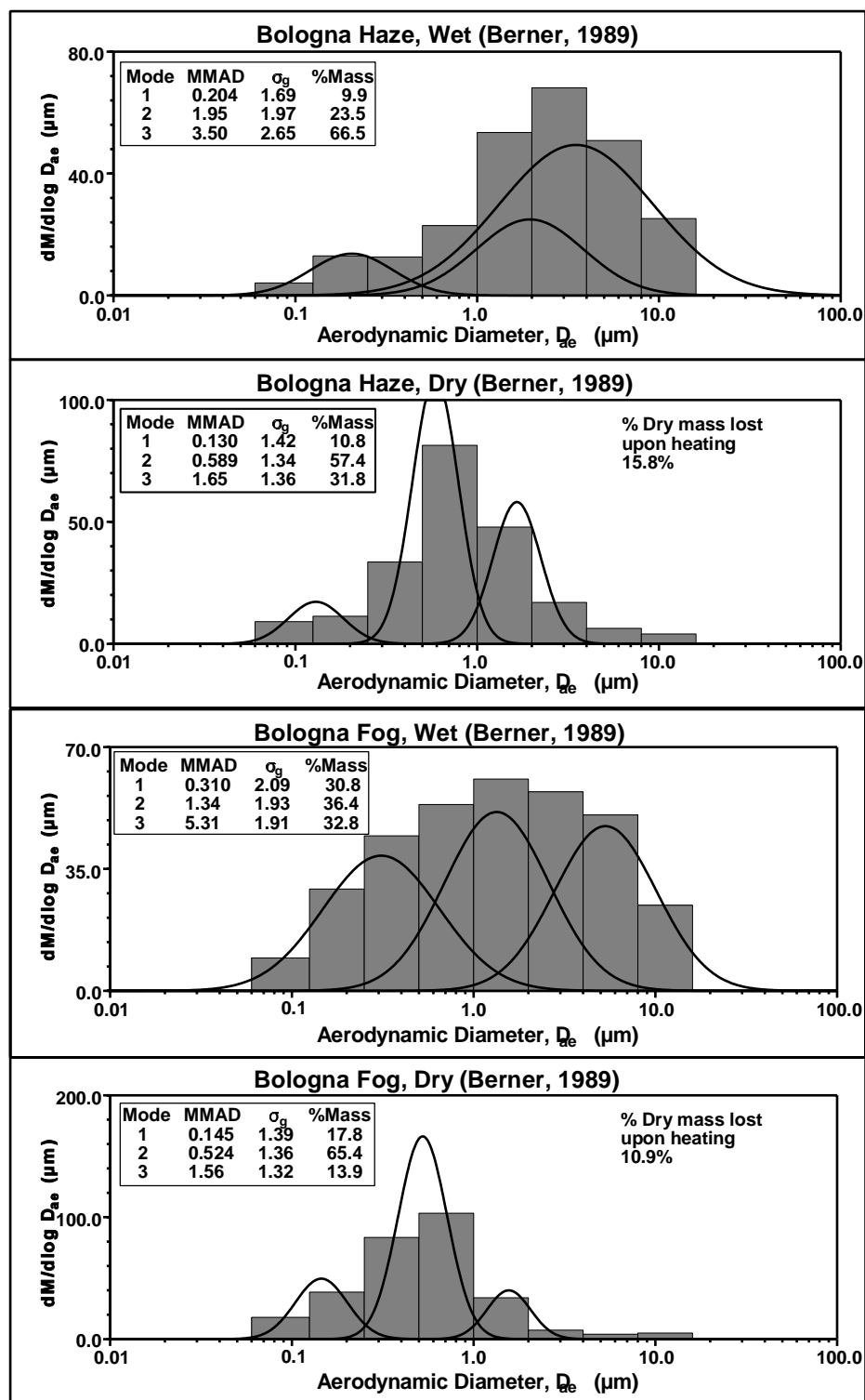


Figure 3-31. Mass size distribution of non-volatile aerosol material. The aerosol was collected at ambient conditions, "wet", or after evaporation of water, "dry".

Source: Berner (1989).

difference. However, researchers have not been nearly as careful in considering temperature and relative humidity effects when measuring size distribution, either with impactors or particle counters, even though effects have been reported in the early literature (Wagman et al., 1967; Sverdrup and Whitby, 1980).

A recent paper by Cass and coworkers (Eldering et al., 1994) provides some insight into how differences in RH resulting from heating can cause differences between particle-counting distributions and impactor distributions. Particle size distributions were obtained by counting particles by mobility (electrical aerosol analyzer) and light scattering (optical particle counter). An example is shown in Figure 3-32. Almost no particles were found between 1.0 and 2.5 μm diameter. When these particle number data were converted to total expected light scattering, they agreed with measurements made by a heated, but not an unheated, integrating nephelometer; and when converted to expected mass, agreed with filter measurements of dry mass. Eldering et al. (1994) conclude that even the moderate heating occurring in mobility and optical counters was enough to change the size of the particles, especially when the ambient air was close to 100% RH. It seems likely that most particle counting systems produce some heating of the aerosol, and thus some reduction of the measured particle size from that existing in the ambient air. On the other hand, if particle-size measuring devices were located in air conditioned or heated trailers or laboratories, the temperature of the sampled air would be changed and the measured particle size distribution would be different from that existing in the ambient air (Sverdrup and Whitby, 1980).

During the high relative humidities that occur at nighttime, growth of hygroscopic components can result in the growth of some fine mode aerosol to diameters greater than 1.0 μm and perhaps even above 2.5 μm . As can be seen in Figure 3-28, dry ammonium sulfate particles having a dry diameter of 0.5 μm will grow to $\approx 2.5 \mu\text{m}$ at a relative humidity between 99 and 100%. When the relative humidity actually reaches 100%, the particles will continue to grow to maintain the relative humidity at 100%, and eventually become fog droplets that are large enough to be collected in the fraction larger than 2.5 μm . Ammonium sulfate particles with dry sizes greater than 0.5 μm would also grow into the larger than 2.5 μm size range.

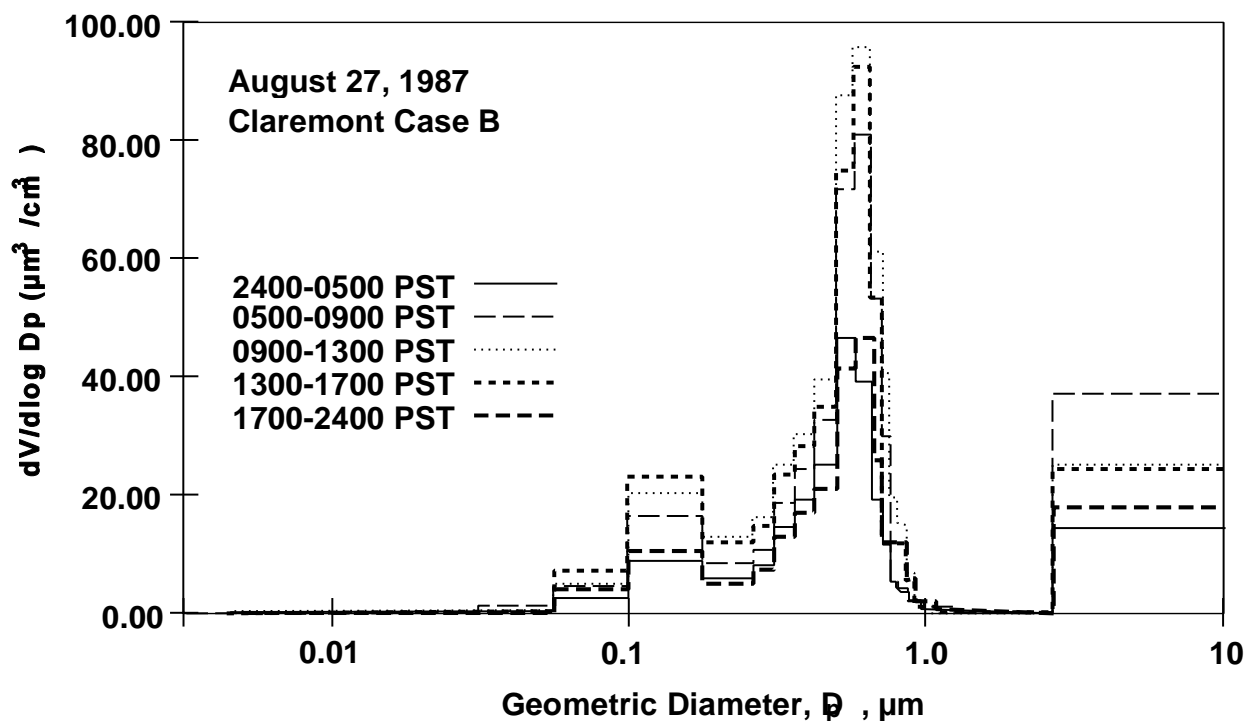


Figure 3-32. Example of particle-counting volume distribution obtained in Claremont, CA. Compare to Figures 3-14 and 3-31. Heating of the sampled air by the mobility and optical counters are believed to have resulted in a distribution representative of a lower than ambient relative humidity.

Source: Eldering et al. (1994).

The addition of water to hygroscopic particles, discussed in the previous section, is a reversible process. Particles absorb water and grow as RH increases; as RH decreases some of the particle-bound water evaporates and the particles shrink. However, the large amount of liquid water associated with hygroscopic particles at high relative humidity provides a medium for liquid phase transformation process. A number of atmospheric process, which convert SO_2 to sulfate or NO_x to nitrate, can take place in water solutions but not in the gas phase. These processes are not reversible but lead to an accumulation of sulfate or nitrate and lead to an increase in the dry size of the particle. Of course as more sulfate or nitrate is added to the particle it will absorb more water so that the wet size will also increase.

The first observation and clear discussion of these combined effects of relative humidity on growth and SO_2 conversion to sulfate are given by Hering and Friedlander (1982) as shown in

Table 3-18. Using a low pressure impactor, they observed that days with higher relative humidity had higher sulfate concentration and higher MMAD's compared to days with lower relative humidity. Hering and Friedlander (1982) named the small mode the condensation mode and suggested that it was formed by the gas phase conversion of SO₂ to sulfate and subsequent nucleation, coagulation, and growth by condensation. They named the larger mode the droplet mode and discussed possible formation mechanisms. This mode is now believed to result from the reaction of SO₂ in fog or cloud droplets (Meng and Seinfeld, 1994).

**TABLE 3-18. COMPARISON OF SULFATE CONCENTRATION
AND MASS MEAN DIAMETERS OF AEROSOLS FOR DAYS
WITH HIGHER AND LOWER RELATIVE HUMIDITY**

	Low RH Days	High RH Days
Minimum RH, %	17 - 35	26 - 66
Maximum RH, %	45 - 68	69 - 100
Sulfate concentration, $\mu\text{g}/\text{m}^3$	3 - 9	3 - 52
Mass median aerodynamic diameter, μm	0.20 ± 0.02	0.54 ± 0.07

Source: Hering and Friedlander (1982).

In a series of papers McMurry and co-workers make use of the aerosol growth law, originally developed by Heisler and Friedlander (1977), to study the mechanism and rates of sulfate formation in ambient air (McMurry et al., 1981; McMurry and Wilson, 1982, 1983). They were able to apportion growth to condensation and droplet mechanisms and observed droplet growth in particles up to 3 μm in diameter.

A process of aerosol growth due to increasing relative humidity (Figure 3-33) has also been utilized by Cahill et al. (1990) to explain observations of sulfate size changes during the 1986 Carbonaceous Species Methods Comparison Study in Glendora, CA. Cahill used a DRUM sampler to measure sulfate in nine size ranges. By tracking the mass of sulfate in the 0.56 to 1.15 μm size range Cahill et al. could follow the expansion and contraction of aerosol particles containing sulfate. Because of the relative high time resolution of the DRUM sampler (4 h except for an 8-h increment each night from midnight to 8 a.m.),

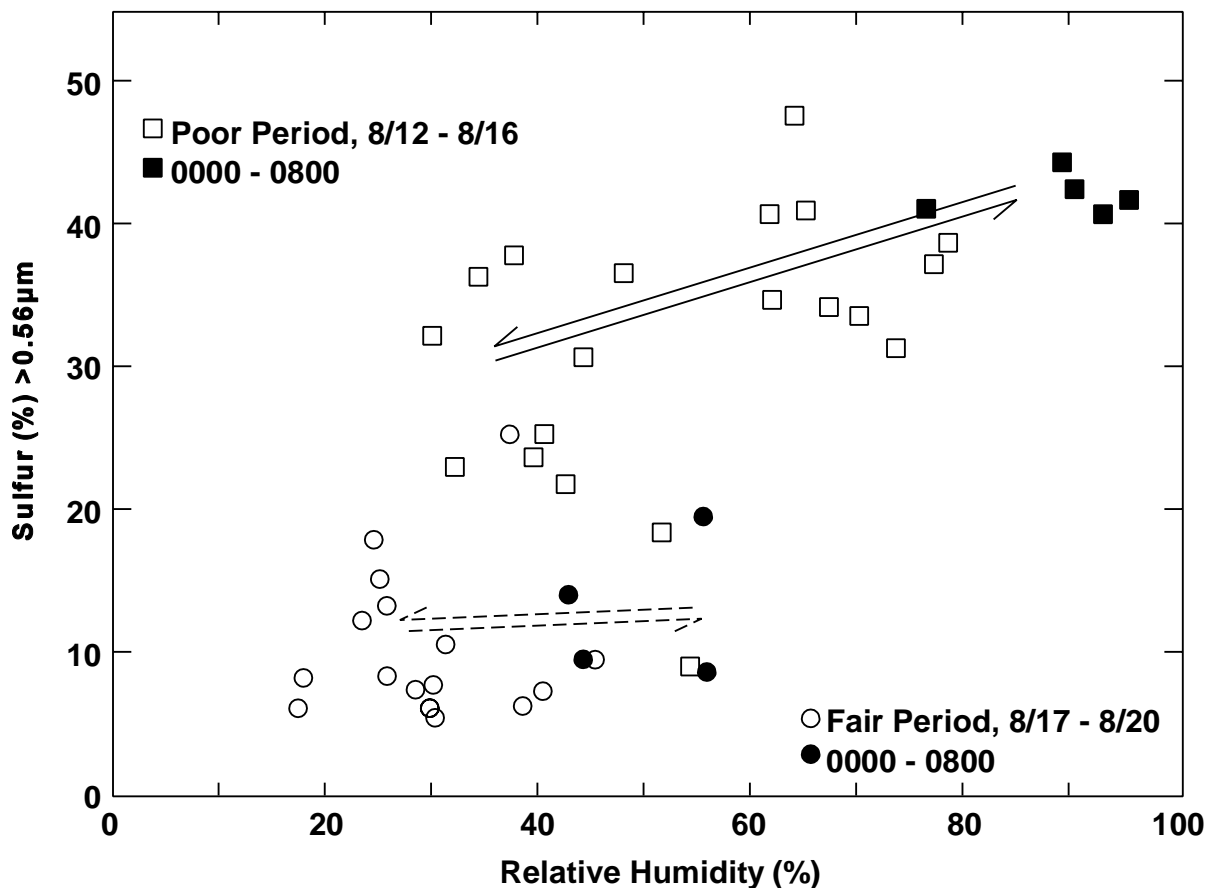


Figure 3-33. Relative humidity versus sulfur, during the 1986 Carbonaceous Species Methods Comparison Study, for particles with $D_{ac} > 0.56 \mu\text{m}$. The approximate trajectories followed during each day by the $D_{ac} > 0.56 \mu\text{m}$ sulfur size fraction are shown for period P and period F. Note that even when the humidities are low, 30 to 50 %, the period P aerosols remain coarser by a factor of three than those of period F. The water content incorporated in the aerosols during the 0000- to 0800-h time periods is lost only slowly, giving a strong hysteresis effect in sulfur size.

Source: Cahill et al. (1990).

Cahill et al. (1990) could follow this process as the relative humidity increased during the night and decreased during the day. These data indicate that during the "Poor Period" (low visibility) particles grow as relative humidity increases. However, they did not return to the smaller size observed during the "Fair Period" (good visibility). This could be due to a combination of growth due to reaction of SO_2 to sulfate within the particles or failure of the droplet to crystallize thus maintaining particle-bound water in a supersaturated state.

John et al. (1990), in studies in the Los Angeles area, observed a number of sulfate size distributions with MMAD near $1.0\ \mu\text{m}$. A histogram of the sulfate MMADs from his study is shown in Figure 3-34. John et al. (1990) have provided a qualitative explanation to account for these large MMADs for fine mode aerosol. In analyzing their data John et al. plotted sulfate mass as a function of sulfate MMAD and found two distinct regions, as shown in Figure 3-35. Distributions with particles near $0.2\ \mu\text{m}$ diameter are probably still dry; the particles have not reached their deliquescent point. As the relative humidity increases they reach their deliquescent point and grow rapidly into the 0.5 to $0.7\ \mu\text{m}$ size range. During the formation of fog, the hygroscopic particles act as fog condensation nuclei, and with relative humidity at 100%, grow into 1 to $10\ \mu\text{m}$ fog droplets. Sulfur dioxide dissolves in the fog droplets and is rapidly oxidized to sulfate by atmospheric oxidants such as H_2O_2 or O_3 , or by catalysis by Fe or Mn. These particles lose some of their water as the relative humidity decreases below 100% RH, but will have substantially more sulfate than prior to activation. Similar processes occur in clouds (Schwartz, 1984a, 1986a).

This type of process probably accounts for the large size of the fine mode observed in Vienna (Berner et al., 1979; Berner and Lürzer, 1980). Winter and summer size distributions are shown in Figure 3-36. Berner et al. reported that fog occurred during the night time during the winter study. In this European study, as in American studies, instances of fine mode size distributions with MMADs near or above $1\ \mu\text{m}$ seem to occur only when fog or very high relative humidity conditions have been present. Two log-normal distributions are fit to the accumulation mode to suggest the separation, at high relative humidity, into hygroscopic and hydrophobic components. No distribution was fit to the coarse mode because only a fraction of the coarse size range was measured.

Similar results have been observed in sampling with dichotomous samplers. A large humidity driven shift of normally fine mode material into the coarse mode was observed by Keeler et al. (1988). In the extreme case, 60% of the SO_4^{2-} and 50% of the $\text{PM}_{2.5}$ mass was shifted to the coarse fraction. Such occurrences were not rare, occurring in 12 out of 83 several-hour sampling periods.

In an analysis of data from the IMPROVE network Cahill and co-workers (Eldred et al., 1994) report that 20% of the total sulfate is found in the coarse fraction of PM_{10} . Studies in Philadelphia using dichotomous samplers have also reported that 20% of the total

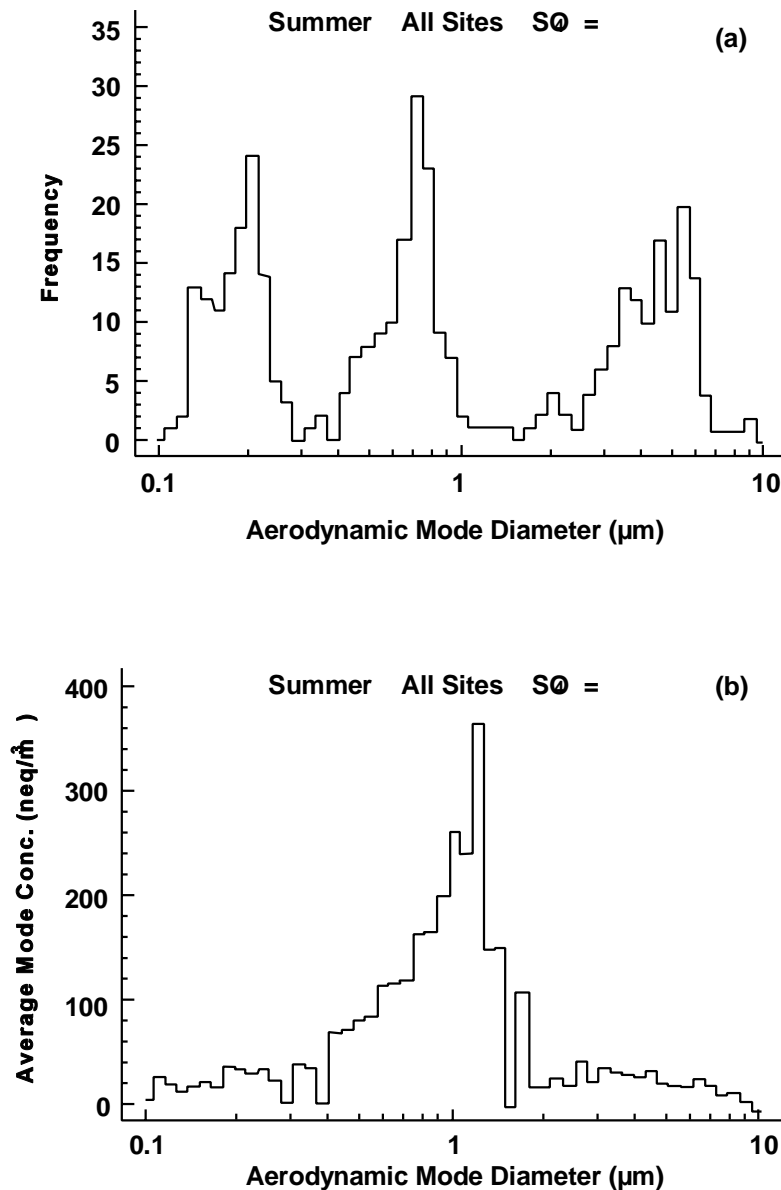


Figure 3-34. Data from the South Coast Air Quality Study (John et al., 1990). Plots show (a) frequency of sulfate modes of various sizes as a function of mode diameter and (b) average sulfate mode concentration as a function of mode diameter. Note that although there are only a few instances when the mode diameter is near $1.0\ \mu\text{m}$, it is these situations that give rise to the highest sulfate concentrations. Modes with diameters above $2.5\ \mu\text{m}$ may be due to collection of fog droplets containing sulfate or reaction of SO_2 in liquid droplets of NaCl due to NaCl sea spray droplets in which SO_2 has dissolved and reacted to form sulfate and release HCl gas.

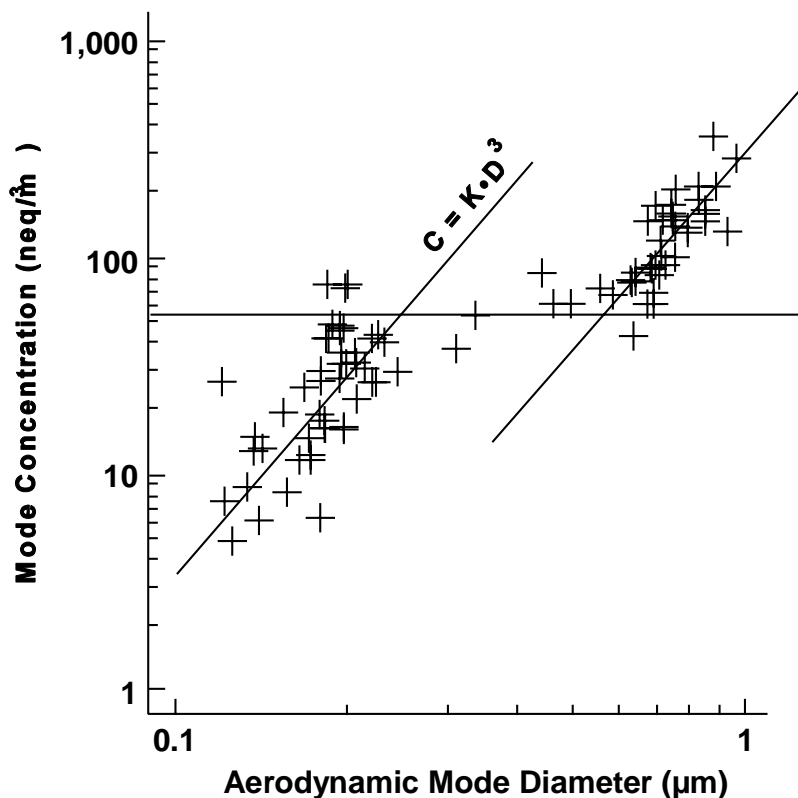


Figure 3-35. Log-log plot of sulfate mode concentration versus aerodynamic mode diameter from Claremont, CA, during the summer SCAQS (John et al., 1990). The solid lines have slopes corresponding to mode concentration increasing with the cube of the mode diameter. A transition between the two modes is believed to occur at approximately the sulfate mode concentration indicated by the horizontal dashed line.

sulfate is found in the coarse fraction (Dzubay et al., 1988). Cahill and coworkers suggest that sulfate particles may grow larger than $2.5\ \mu\text{m}$ in diameter and thus be sampled in the PM_{10} fraction but not the $\text{PM}_{2.5}$ fraction. It is possible for SO_2 to react with basic carbonate coarse particles to form a sulfate coating or to dissolve in wet NaCl particles, from oceans, lakes, or salt placed on streets to dissolve ice, and be converted to sulfate with the release of HCl. However, there also is substantial evidence that some fine sulfate, and therefore possibly other fine mode material, may be found in the size range above $1.0\ \mu\text{m}$ and even

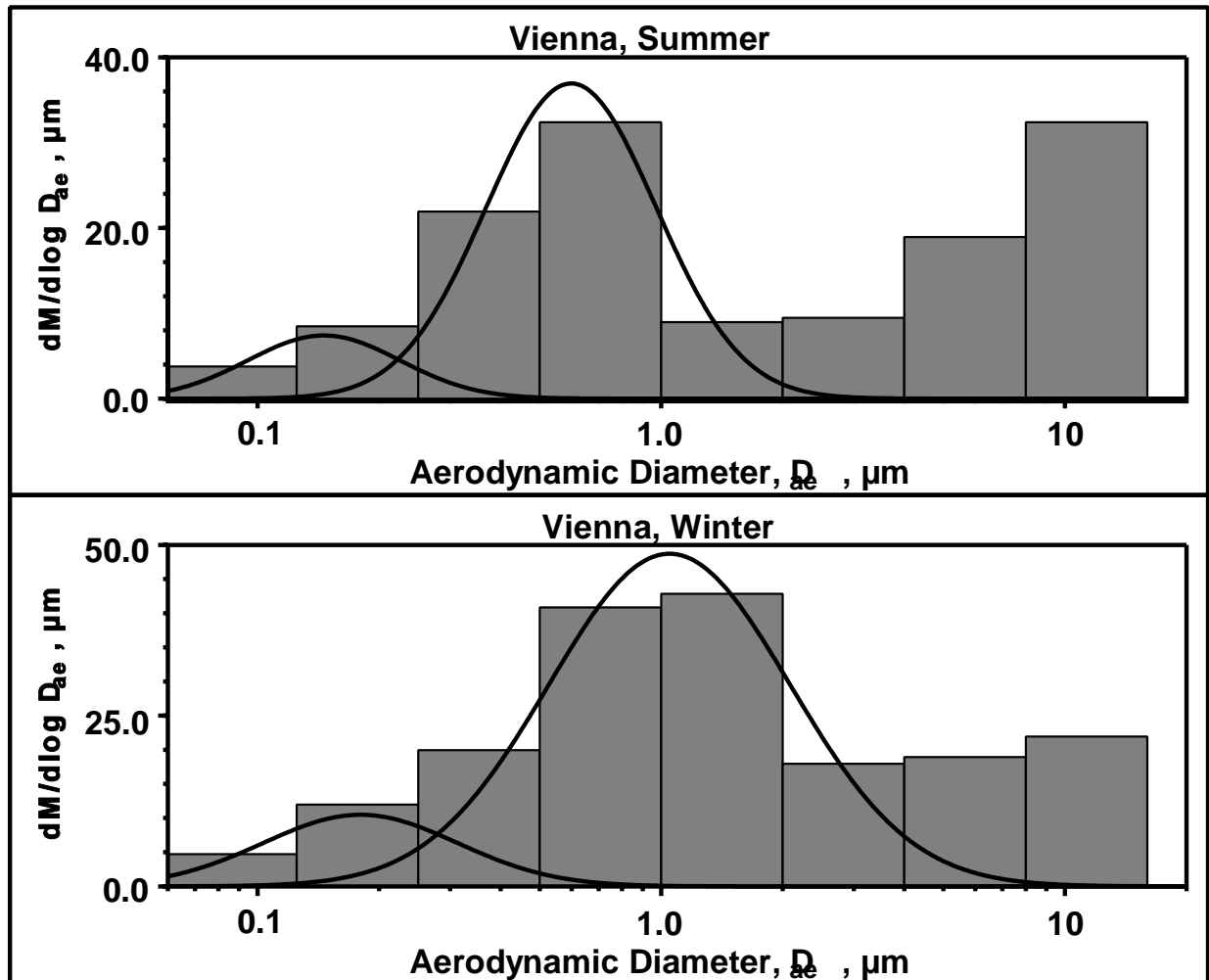


Figure 3-36. Typical results of size-distribution measurements taken with a Berner impactor in a Vienna street with heavy automotive traffic: (a) measurements taken during summer at three different elevations, (b) measurements taken during winter at three different elevations, fog was frequently present during the winter sampling period.

Source: Berner and Lürzer (1980).

above $2.5 \mu\text{m}$ diameter, due to the growth of hygroscopic particles at very high relative humidity.

These observations, indicating that, during near 100% relative humidity conditions, significant amounts of normally fine mode material will be found in the coarse fractions ($>2.5 \mu\text{m}$ diameter), have broader implications than selection of a cut point to separate fine and coarse

particles. Such shifts could cause problems for receptor modeling using chemical mass balance or factor analysis, for interpretation of exposure data in epidemiological studies, and in estimated removal of particulate matter by deposition.

3.7.7 Conclusions

This review of atmospheric particle-size-distributions was undertaken to provide information which could be used to determine what cut-point; $1.0\ \mu\text{m}$, $2.5\ \mu\text{m}$, or something in between; would give the best separation between the fine and coarse particle modes. The data do not provide a clear or obvious answer. Depending on conditions, a significant amount of either fine or coarse mode material may be found in the intermodal region between 1.0 and $3\ \mu\text{m}$. However, the analysis does demonstrate the important role of relative humidity in influencing the size of the fine particle mode and indicates that significant fine mode material is found above $1.0\ \mu\text{m}$ only during periods of very high relative humidity.

Thus, a $\text{PM}_{2.5}$ sample will contain most of the fine mode material, except during periods of RH near 100 %. However, especially in conditions of low RH, it may contain 5 to 20 % of the coarse mode material below $10\ \mu\text{m}$ in diameter. A $\text{PM}_{1.0}$ sample will prevent misclassification of coarse mode material as fine but under high RH conditions will result in some of the fine mode material being misclassified as coarse.

A reduction in RH, either intentionally or inadvertently, will reduce the size of the fine mode. A sufficient reduction in RH will yield a dry fine particle mode with very little material above $1.0\ \mu\text{m}$. However, reducing the RH by heating will result in loss of semivolatile components such as ammonium nitrate and semivolatile organic compounds. No information was found on techniques designed to remove particle-bound water without loss of other semivolatile components.

3.8 SUMMARY

Atmospheric particulate matter (PM) refers to solid or liquid particles suspended in air. The term atmospheric aerosol refers to both the suspended particles and the air (including gaseous pollutants) in which the particles are suspended. However, the term aerosol is

frequently used to refer only to the suspended particles. The terms particulate matter and particles will be used most frequently in this document.

Particulate matter is not a single pollutant but rather a mixture of many classes of pollutants. The components of PM differ in sources; formation mechanisms; composition; size; and chemical, physical, and biological properties. Particle diameters span more than four orders of magnitude, ranging from a few nanometers (nm) to one hundred micrometers (μm). Because of this wide size range, plots of particle-size distribution are almost always plotted versus the logarithm of the particle diameter. Diameter usually refers to the aerodynamic diameter, defined as the diameter of a spherical particle with an equal settling velocity but a density of 1 g/cm^3 . This normalizes particles of different shapes and densities.

One of the most fundamental divisions of atmospheric particles is the naturally occurring separation into a fine particle mode and a coarse particle mode as shown in Figure 3-3. The terms fine mode particles and coarse mode particles are used to refer to particles in the fine or coarse particle distributions. The two distributions overlap between 1 and $3\text{ }\mu\text{m}$ aerodynamic diameter.

Particles may also be defined by the size cut of the collection or measuring device. A frequently used descriptor is the 50% cut point. This is the aerodynamic diameter at which the efficiency of the device for particle collection is 50%. As particles increase in size above the 50% cut point, they are collected with decreasing efficiency, eventually reaching 0%; as particles decrease in size below the 50% cut point, they are collected with increasing efficiency, eventually reaching 100%. The indicator for the current particle standard is PM_{10} (i.e. particles with a 50% cut point of $10\text{ }\mu\text{m}$ aerodynamic diameter). However, PM_{10} contains some particles larger than $10\text{ }\mu\text{m}$ and does not contain all particles below $10\text{ }\mu\text{m}$. Fine is also used to refer to particles with an upper cut point of 3.5, 2.5 ($\text{PM}_{2.5}$), 2.1, or $1.0\text{ }\mu\text{m}$. Coarse is also used to refer to particles between 2.5 and $10\text{ }\mu\text{m}$ ($\text{PM}_{(10-2.5)}$) or particles collected by the high volume sampler as well as the entire coarse mode.

Size fractions may also be characterized in terms of their entrance into various compartments of the body. Thus, inhalable particles enter the respiratory tract, including the head airways. Thoracic particles travel past the larynx and reach the lung airways and the gas-exchange regions of the lung. Respirable particles reach the gas-exchange region of the lung.

PM₁₀ is an indicator of thoracic particles; PM_{2.5} is an indicator of fine mode particles; and PM_(10-2.5) is an indicator of the thoracic component of coarse mode particles.

The fine and coarse particle distributions are frequently approximated by log-normal distributions. However, finer distinctions can be made. The fine particles consist of a nuclei mode, composed of particles recently formed from gases, and an accumulation mode, into which the nuclei grow and accumulate (Figure 3-6). Ultrafine particles, defined in this document as distributions with mass median diameters below 0.1 μm , are associated with the nuclei mode (Figures 3-1, 3-2, and 3-13). In the presence of fogs or clouds, the accumulation mode may split into a smaller, less hygroscopic mode and a larger droplet mode. The latter is formed by gases dissolving in the fog or cloud droplets, reacting, and forming particles when the water of the droplets evaporates (Figure 3-14). There may also be several modes within the coarse particle distribution or mode but these are usually less distinct.

The terms primary and secondary, anthropogenic and biogenic, outdoor and indoor microenvironment have significant applications to particulate matter. Primary fine particles are emitted from sources, either directly as particles or as vapors which rapidly condense to form particles. Primary coarse particles are usually formed by mechanical processes. Secondary fine particles are formed within the atmosphere as the result of gas-phase or aqueous-phase chemical reactions. Anthropogenic particles may be formed by primary or secondary processes. Similarly, biogenic particles include primary particles of biological origin, including bioallergens, as well as secondary particles formed from biogenic precursors such as terpenes emitted into the atmosphere. The term outdoor refers to community atmospheres. These are the atmospheres which are usually monitored for particulate matter. Indoor microenvironments include homes, apartments, schools, office buildings and other indoor work places, large enclosed areas such as malls, vehicles used for commuting, etc.

Some general classes of particles, such as organic particles, can occur not only as fine or coarse particles, but can be of either anthropogenic and biogenic origin, and can be produced both in outdoor and indoor microenvironments. Organic particles also can be present in air as primary fine particles from combustion processes or as secondary fine particles formed as a result of atmospheric reactions involving higher molecular weight volatile anthropogenic

alkenes and aromatics or from the atmospheric reactions of volatile biogenic compounds such as terpenes. Therefore, there is considerable overlap for chemical species among the categories listed above.

A substantial fraction of the fine particle mass, especially during the warmer months of the year, is secondary PM, formed as a result of atmospheric reactions. Such reactions involve the gas phase conversion of SO_2 to H_2SO_4 by OH radicals and aqueous-phase reactions of SO_2 with H_2O_2 , O_3 , or O_2 (catalyzed by Fe and Mn). The NO_2 portion of NO_x can be converted to HNO_3 by reaction with OH radicals during the day. During nighttime NO_2 is converted into HNO_3 by a series of reactions involving O_3 and the nitrate radical (NO_3). Both H_2SO_4 and HNO_3 react with atmospheric ammonia (NH_3). Gaseous NH_3 reacts with gaseous HNO_3 to form particulate NH_4NO_3 . Gaseous NH_3 reacts with H_2SO_4 to form acidic HSO_4^- and neutral $(\text{NH}_4)_2\text{SO}_4$. A number of volatile organic compounds can react with O_3 and/or OH radical to form fine organic particles. In addition, acid gases such as SO_2 and HNO_3 may react with coarse particles such as CaCO_3 and NaCl to form coarse particles of different chemical composition.

The concentrations of OH radicals, O_3 , and H_2O_2 , formed by gas phase reactions involving volatile organic compounds and NO_x , depend on the concentrations of the reactants, and on meteorological conditions including temperature, solar radiation, wind speed, mixing volume and passage of high pressure systems. Therefore, formation of a substantial fraction of fine particles can depend on the gas phase reactions which also produce O_3 and a variety of other volatile products.

The fine particle fraction, in addition to SO_4^{2-} and NO_3^- , contains elemental carbon (EC), organic carbon (OC), H^+ (hydrogen ions or acidity) and a number of metal compounds at lower concentrations. Species such as SO_4^{2-} , NO_3^- and some organic species are associated with substantial amounts of particle-bound water. NH_4NO_3 is in equilibrium with HNO_3 and NH_3 so it can vaporize from particles. Organic particles can also be in equilibrium with their vapor. Such species are called semi-volatile. A number of trace elements including, but not necessarily limited to, Pb, Zn, Ni, Cd, Na, Cl, Br, Se and As have been measured in the $\text{PM}_{2.5}$ fraction of fine particles. The coarse particles are largely composed of the crustal elements Si, Ca, Al, and Fe. However, a considerable number of elements are found in both the fine and coarse fractions.

Chemical reactions of SO_2 and NO_x within plumes are an important source of H^+ , SO_4 and NO_3^- . These conversions can occur by gas-phase and aqueous-phase mechanisms.

In point-source plumes emitting SO_2 and NO_x , the gas-phase chemistry depends on plume dilution, sunlight and background volatile organic compounds mixed into the diluting plume. For the conversion of SO_2 to H_2SO_4 , the gas-phase rate in such plumes during summer midday conditions in the eastern United States typically varies between 1 and 3% h^{-1} but in the cleaner western United States rarely exceeds 1% h^{-1} . For the conversion of NO_x to HNO_3 , the gas-phase rates appear to be approximately three times faster than the SO_2 conversion rates. Winter rates for SO_2 conversion were approximately an order of magnitude lower than the summer rates.

The contribution of aqueous-phase chemistry to particle formation in point-source plumes is highly variable, depending on the availability of the aqueous phase (wetted aerosols, clouds, fog, and light rain) and the photochemically generated gas-phase oxidizing agents, especially H_2O_2 for SO_2 chemistry. The in-cloud conversion rates of SO_2 to $\text{SO}_4^{=}$ can be several times larger than the gas-phase rates given above. Overall, it appears that SO_2 oxidation rates to $\text{SO}_4^{=}$ by gas-phase and aqueous-phase mechanisms may be comparable in summer, but aqueous phase chemistry may dominate in winter.

In the western United States, markedly higher SO_2 conversion rates have been reported in smelter plumes than in power plant plumes. The conversion is predominantly by a gas-phase mechanism. This result is attributed to the lack of NO_x in smelter plumes. In power plant plumes NO_2 depletes OH and competes with SO_2 for OH.

In urban plumes, the upper limit for the gas-phase SO_2 conversion rate appears to be about 5% h^{-1} under the more polluted conditions. For NO_2 , the rates appear to be approximately three times faster than the SO_2 conversion rates. Conversion rates of SO_2 and NO_x in background air are comparable to the peak rates in diluted plumes. Neutralization of H_2SO_4 formed by SO_2 conversion increases with plume age and background NH_3 concentration. If the NH_3 concentrations are more than sufficient to neutralize H_2SO_4 to $(\text{NH}_4)_2\text{SO}_4$, the HNO_3 formed from NO_x conversions may be converted to NH_4NO_3 .

The lifetimes of particles vary with size. Coarse particles can settle rapidly from the atmosphere within hours, and normally travel only short distances. However, when mixed high into the atmosphere as in dust storms the smaller sized coarse mode particles may have longer lives and travel distances. Nuclei mode particles rapidly grow into the accumulation mode. However, the accumulation mode does not grow into the coarse mode. Accumulation-mode fine particles are kept suspended by normal air motions and have very low deposition rates to

surfaces. They can be transported thousands of km and remain in the atmosphere for a number of days. Both accumulation-mode and nuclei-mode (or ultrafine) particles have the ability to penetrate deep into the lungs. Dry deposition rates are expressed in terms of a deposition velocity which varies as the particle size, reaching a minimum between 0.1 and 1.0 μm aerodynamic diameter. Accumulation-mode particles are removed from the atmosphere primarily by cloud processes. Fine particles, especially particles with a hygroscopic component, grow as the relative humidity increases, serve as cloud condensation nuclei, and grow into cloud droplets. If the cloud droplets grow large enough to form rain, the particles are removed in the rain. Falling rain drops impact coarse particles and remove them. Ultrafine or nuclei mode particles are small enough to diffuse to the falling drop and be removed. Falling rain drops, however, are not effective in removing accumulation-mode particles.

There are many reasons for wanting to collect fine and coarse particles separately. However, because fine-mode particles and coarse-mode particles overlap in the size range between 1.0 and 3 μm diameter, it is not clear what 50% cut point will give the best separation.

A review of atmospheric particle-size-distribution data did not provide a clear or obvious answer. Depending on conditions, a significant amount of either fine or coarse mode material may be found in the intermodal region between 1.0 and 3 μm . However, the analysis of the existing data did demonstrate the important role of relative humidity in influencing the size of the fine particle mode and indicated that significant fine mode material is found above 1.0 μm only during periods of very high relative humidity.

Thus, a $\text{PM}_{2.5}$ sample will contain most of the fine mode material, except during periods of RH near 100 %. However, especially in conditions of low RH, it may contain 5 to 20 % of the coarse mode material below 10 μm in diameter. A $\text{PM}_{1.0}$ sample will prevent misclassification of coarse mode material as fine but under high RH conditions will result in some of the fine mode material being misclassified as coarse.

A reduction in RH, either intentionally or inadvertently, will reduce the size of the fine mode. A sufficient reduction in RH will yield a dry fine particle mode with very little material above 1.0 μm . However, techniques to reduce the RH without loss of semivolatile components such as ammonium nitrate and semivolatile organic compounds have not yet been developed.

REFERENCES

- Adamson, A. W. (1976) Physical chemistry of surfaces New York, NY: John Wiley & Sons, Inc.
- Akhter, M. S.; Chughtai, A. R.; Smith, D. M. (1984) Reaction of hexane soot with $\text{NO}_2/\text{N}_2\text{O}_4$. *J. Phys. Chem.* 88: 5334-5342.
- Akhter, M. S.; Chughtai, A. R.; Smith, D. M. (1985) The structure of hexane soot I: spectroscopic studies. *Appl. Spectrosc.* 39: 143-153.
- Aleic-Juretic, A.; Cvitas, T.; Klasinc, L. (1990) Heterogeneous polycyclic aromatic hydrocarbon degradation with ozone on silica gel carrier. *Environ. Sci. Technol* 24: 62-66.
- Alkezweeny, A.; Powell, D. (1977) Estimation of transformation rate of SO_2 to SO_4 from atmospheric concentration data. *Atmos. Environ.* 11: 179-182.
- Allen, D. T.; Palen, E. J.; Haimov, M. I.; Hering, S. V.; Young, J. R. (1994) Fourier transform infrared spectroscopy of aerosol collected in a low pressure impactor (LPI / FTIR): method development and field calibration. *Aerosol Sci. Technol.* 21: 325-342.
- Allwine, K. J. (1993) Atmospheric dispersion and tracer ventilation in a deep mountain valley. *J. Appl. Meteorol.* 32: 1017-1037.
- Alofs, D. J.; Hagen, D. E.; Trueblood, M. B. (1989) Measured spectra of the hygroscopic fraction of atmospheric aerosol particles. *J. Appl. Meteorol.* 28: 126-136.
- Altshuller, A. P. (1983) Review: natural volatile organic substances and their effect on air quality in the United States. *Atmos. Environ.* 17: 2131-2165.
- Altshuller, A. P. (1987) Potential contribution of sulfate production in cumulus cloud droplets to ground level particle sulfur concentrations. *Atmos. Environ.* 21: 1097-1105.
- American Conference of Governmental Industrial Hygienists (ACGIH). (1994) Appendix D: particle size-selective sampling criteria for airborne particulate matter. In: 1994-1995 threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH: American Conference of Governmental Industrial Hygienists; pp. 43-46.
- Anderson, J. R.; Aggett, F. J.; Buseck, P. R.; Germani, M. S.; Shattuck, T. W. (1988) Chemistry of individual aerosol particles from Chandler, Arizona, an arid urban environment. *Environ. Sci. Technol.* 22: 811-818.
- Andreae, M. O.; Charlson, R. J.; Bruynseels, F.; Storms, H.; Van Grieken, R.; Maenhaut, W. (1986) Internal mixture of sea salt, silicates, and excess sulfate in marine aerosols. *Science (Washington, DC)* 232: 1620-1623.
- Andrews, E.; Larson, S. M. (1993) Effect of surfactant layers on the size changes of aerosol particles as a function of relative humidity. *Environ. Sci. Technol.* 27: 857-865.
- Appel, B. R.; Tokiwa, Y.; Hsu, J.; Kothny, E. L.; Hahn, E. (1985) Visibility as related to atmospheric aerosol constituents. *Atmos. Environ.* 19: 1525-1534.
- Appel, B. R.; Cheng, W.; Salaymeh, F. (1989) Sampling of carbonaceous particles in the atmosphere—II. *Atmos. Environ.* 23: 2167-2175.
- Arimoto, R.; Duce, R. A.; Ray, B. J.; Unni, C. K. (1985) Atmospheric trace elements at Enewetak Atoll: 2. transport to the ocean by wet and dry deposition. *J. Geophys. Res. [Atmos.]* 90: 2391-2408.

- Arnts, R. R.; Gay, B. W., Jr. (1979) Photochemistry of some naturally emitted hydrocarbons. Research Triangle Park, NC: U.S. Environmental Protection Agency, Environmental Sciences Research Laboratory; EPA report no. EPA-600/3-79-081. Available from: NTIS, Springfield, VA; PB80-131980.
- Atkinson, R.; Aschmann, S. M. (1987) Kinetics of the gas-phase reactions of alkylnaphthalenes with O_3 , N_2O_5 and OH radicals at 298 ± 2 K. *Atmos. Environ.* 21: 2323-2326.
- Avissar, R.; Pielke, R. A. (1989) A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology. *Mon. Weather Rev.* 117: 2113-2136.
- Ayers, G. P.; Larson, T. V. (1990) Numerical study of droplet size dependent chemistry in oceanic, wintertime stratus clouds at southern mid-latitudes. *J. Atmos. Chem.* 11: 143-167.
- Baek, S. O.; Field, R. A.; Goldstone, M. E.; Kirk, P. W.; Lester, J. N.; Perry, R. (1991) A review of atmospheric polycyclic aromatic hydrocarbons: sources, fate and behavior. *Water Air Soil Pollut.* 60: 279-300.
- Bagnold, R. A. (1941) The physics of blown sand and desert dunes. London, United Kingdom: Methuen & Co.
- Baker, M. B.; Latham, J. (1979) The evolution of droplet spectra and the rate of production of embryonic raindrops in small cumulus clouds. *J. Atmos. Sci.* 36: 1612-1615.
- Baldwin, A. C. (1982) Heterogeneous reactions of sulfur dioxide with carbonaceous particles. *Int. J. Chem. Kinet.* 14: 269-277.
- Barnard, W. R.; Gatz, D. F.; Stensland, G. J. (1987) Chemical characterization of aerosols emitted from vehicle traffic on unpaved roads. Presented at: 80th annual meeting of the Air Pollution Control Association; June; New York, NY. Pittsburgh, PA: Air Pollution Control Association; paper no. 87-14.3.
- Barnard, W. R.; Stansland, G. J.; Gatz, D. F. (1988) Flux of alkaline materials from unpaved roads in the southwestern United States. In: Particulate matter/fugitive dusts: measurement and control in western arid regions. Proceedings of an Air Pollution Control Association meeting. Pittsburgh, PA: Air Pollution Control Association; pp. 27-39.
- Barrie, L. A. (1985) Scavenging ratios, wet deposition, and in-cloud oxidation: an application to the oxides of sulphur and nitrogen. *J. Geophys. Res. [Atmos.]* 90: 5789-5799.
- Barrie, L. A.; Georgii, H. W. (1976) An experimental investigation of the absorption of sulphur dioxide by water drops containing heavy metal ions. *Atmos. Environ.* 10: 743-749.
- Barth, M. C. (1994) Numerical modeling of sulfur and nitrogen chemistry in a narrow cold-frontal rainband: the impact of meteorological and chemical parameters. *J. Appl. Meteorol.* 33: 855-868.
- Barth, M. C.; Hegg, D. A.; Hobbs, P. V. (1992) Numerical modeling of cloud and precipitation chemistry associated with two rainbands and some comparisons with observations. *J. Geophys. Res. [Atmos.]* 97: 5825-5845.
- Bassett, M.; Seinfeld, J. H. (1983) Atmospheric equilibrium model of sulfate and nitrate aerosols. *Atmos. Environ.* 17: 2237-2252.
- Bassett, M. E.; Seinfeld, J. H. (1984) Atmospheric equilibrium model of sulfate and nitrate aerosols - II. particle size analysis. *Atmos. Environ.* 18: 1163-1170.
- Behymer, T. D.; Hites, R. A. (1988) Photolysis of polycyclic aromatic hydrocarbons adsorbed on fly ash. *Environ. Sci. Technol.* 22: 1311-1319.

- Benkovitz, C. M.; Berkowitz, C. M.; Easter, R. C.; Nemesure, S.; Wagener, R.; Schwartz, S. E. (1994) Sulfate over the North Atlantic and adjacent continental regions: evaluation for October and November 1986 using a three-dimensional model driven by observation-derived meteorology. *J. Geophys. Res. [Atmos.]* 99: 20,725-20,756.
- Benner, C. L.; Eatough, D. J.; Eatough, N. L.; Bhardwaja, P. (1991) Comparison of annular denuder and filter pack collection of HNO_3 (g), HNO_2 (g), SO_2 (g), and particulate-phase nitrate, nitrite and sulfate in the south-west desert. *Atmos. Environ. Part A* 25: 1537-1545.
- Bergstrom, R. W.; Seigneur, C.; Babson, B. L.; Holman, H.-Y.; Wojcik, M. A. (1981) Comparison of the observed and predicted visual effects caused by power plant plumes. *Atmos. Environ.* 15: 2135-2150.
- Berner, A. (1989) Haze and its relation to atmospheric accumulation aerosol. *Sci. Total Environ.* 86: 251-263.
- Berner, A.; Lürzer, C. (1980) Mass size distributions of traffic aerosols at Vienna. *J. Phys. Chem.* 84: 2079-2083.
- Berner, A.; Lürzer, Ch.; Pohl, F.; Preining, O.; Wagner, P. (1979) The size distribution of the urban aerosol in Vienna. *Sci. Total Environ.* 13: 245-261.
- Bernstein, D. M.; Rahn, K. A. (1979) New York Summer Aerosol Study: trace element concentrations as a function of particle size. In: Kneip, T. J.; Lippmann, M., eds. *The New York Summer Aerosol Study, 1976*. Ann. N. Y. Acad. Sci. 322: 87-97.
- Bidleman, T. F. (1988) Atmospheric processes. *Environ. Sci. Technol.* 22: 361-367.
- Biggins, P. D. E.; Harrison, R. M. (1980) Chemical speciation of lead compounds in street dusts. *Environ. Sci. Technol.* 14: 336-339.
- Bjørseth, A.; Olufsen, B. S. (1983) Long-range transport of polycyclic aromatic hydrocarbons. In: Bjørseth, A., ed. *Handbook of polycyclic aromatic hydrocarbons*. New York, NY: Marcel Dekker, Inc.; pp. 507-524.
- Bjørseth, A.; Lunde, G.; Lindskog, A. (1979) Long-range transport of polycyclic aromatic hydrocarbons. *Atmos. Environ.* 13: 45-53.
- Bott, A. (1991) On the influence of the physico-chemical properties of aerosols on the life cycle of radiation fogs. *Boundary Layer Meteorol.* 56: 1-31.
- Bott, A.; Carmichael, G. R. (1993) Multiphase chemistry in a microphysical radiation fog model—a numerical study. *Atmos. Environ. Part A* 27: 503-522.
- Bower, K. N.; Choularton, T. W. (1993) Cloud processing of the cloud condensation nucleus spectrum and its climatological consequences. *Q. J. R. Meteorol. Soc.* 119: 655-679.
- Bower, K. N.; Hill, T. A.; Coe, H.; Choularton, T. W. (1991) SO_2 oxidation in an entraining cloud model with explicit microphysics. *Atmos. Environ. Part A* 25: 2401-2418.
- Boyce, S. D.; Hoffmann, M. R. (1984) Kinetics and mechanism of the formation of hydroxymethanesulfonic acid at low pH. *J. Phys. Chem.* 88: 4740-4746.
- Braaten, D. A.; Paw U, K. T. (1992) A stochastic particle resuspension and deposition model. In: Schwartz, S. E.; Slinn, W. G. N., eds. *Precipitation scavenging and atmosphere-surface exchange: proceedings of the fifth international conference, v. 2: the Semonin volume: atmosphere-surface exchange processes; July 1991*; Richland, WA. Washington, DC: Hemisphere Publishing Corporation; pp. 1143-1152.
- Braaten, D. A.; Paw U, K. T.; Shaw, R. H. (1989) Particles resuspension in a turbulent boundary layer—observed and modeled. *J. Aerosol Sci.* 21: 613-628.

- Brauer, M.; Koutrakis, P.; Keeler, G. J.; Spengler, J. D. (1991) Indoor and outdoor concentrations of inorganic acidic aerosols and gases. *J. Air Waste Manage. Assoc.* 41: 171-181.
- Briggs, G. A.; Binkowski, F. S. (1985) Research on diffusion in atmospheric boundary layers: a position paper on status and needs. Research Triangle Park, NC: U.S. Environmental Protection Agency, Atmospheric Sciences Research Laboratory; EPA report no. EPA/600/3-85/072. Available from: NTIS, Springfield, VA; PB86-122587.
- Brosset, C.; Andreasson, K.; Ferm, M. (1975) The nature and possible origin of acid particles observed at the Swedish west coast. *Atmos. Environ.* 9: 631-642.
- Brown, N. J.; Dod, R. L.; Mowrer, F. W.; Novakov, T.; Williamson, R. B. (1989) Smoke emission factors from medium-scale fires: part 1. *Aerosol Sci. Technol.* 10: 2-19.
- Buat-Ménard, P.; Duce, R. A. (1986) Precipitation scavenging of aerosol particles over remote marine regions. *Nature (London)* 321: 508-510.
- Burkhard, E. G.; Dutkiewicz, V. A.; Husain, L. (1994) A study of SO_2 , SO_4^{2-} and trace elements in clear air and clouds above the midwestern United States. *Atmos. Environ.* 28: 1521-1533.
- Burton, R. M.; Lundgren, D. A. (1987) Wide range aerosol classifier: a size selective sampler for large particles. *Aerosol Sci. Technol.* 6: 289-301.
- Burtscher, H. (1992) Measurement and characteristics of combustion aerosols with special consideration of photoelectric charging and charging by flame ions. *J. Aerosol Sci.* 23: 549-595.
- Burtscher, H.; Leonardi, A.; Steiner, D.; Baltensperger, U.; Weber, A. (1993) Aging of combustion particles in the atmosphere - results from a field study in Zürich. *Water Air Soil Pollut.* 68: 137-147.
- Cadle, S. H.; Dasch, J. M. (1988) Wintertime concentrations and sinks of atmospheric particulate carbon at a rural location in northern Michigan. *Atmos. Environ.* 22: 1373-1381.
- Cahill, T. A.; Surovik, M.; Wittmeyer, I. (1990) Visibility and aerosols during the 1986 Carbonaceous Species Methods Comparison Study. *Aerosol Sci. Technol.* 12: 149-160.
- Calvert, J. G.; Su, F.; Bottenheim, J. W.; Strausz, O. P. (1978) Mechanism of the homogeneous oxidation of sulfur dioxide in the troposphere. In: *Sulfur in the atmosphere: proceedings of the international symposium; September 1977; Dubrovnik, Yugoslavia.* *Atmos. Environ.* 12: 197-226.
- Calvert, J. G.; Lazrus, A.; Kok, G. L.; Heikes, B. G.; Walega, J. G.; Lind, J.; Cantrell, C. A. (1985) Chemical mechanisms of acid generation in the troposphere. *Nature (London)* 317: 27-35.
- Cambray, R. S. (1989) Radioactive fallout in air and rain: results to the end of 1987. Harwell, United Kingdom: Atomic Energy Establishment; report no. AERE-R 13226.
- Cambray, R. S.; Cawse, P. A.; Garland, J. A.; Gibson, J. A. B.; Johnson, P.; Lewis, G. N. J.; Newton, D.; Salmon, L.; Wade, B. O. (1987) Observations on radioactivity from the Chernobyl accident. *Nucl. Energy (Br. Nucl. Energy Soc.)* 26: 77-101.
- Carpenter, S. B.; Montgomery, T. L.; Leavitt, J. M.; Colbaugh, W. C.; Thomas, F. W. (1971) Principal plume dispersion models: TVA power plants. *J. Air Pollut. Control Assoc.* 21: 491-495.
- Carras, J. N.; Williams, D. J. (1981) The long-range dispersion of a plume from an isolated point source. *Atmos. Environ.* 15: 2205-2217.

- Carras, J. N.; Williams, D. J. (1988) Measurements of relative σ_y up to 1800 km from a single source. *Atmos. Environ.* 22: 1061-1069.
- Carter, E. J.; Borys, R. D. (1993) Aerosol-cloud chemical fractionation: enrichment factor analysis of cloud water. *J. Atmos. Chem.* 17: 277-292.
- Cass, G. R. (1979) On the relationship between sulfate air quality and visibility with examples in Los Angeles. *Atmos. Environ.* 13: 1069-1084.
- Cass, G. R.; Shair, F. H. (1984) Sulfate accumulation in a sea breeze/land breeze circulation system. *J. Geophys. Res.* [Atmos.] 89: 1429-1438.
- Cass, G. R.; Boone, P. M.; Macias, E. S. (1982) Emissions and air quality relationships for atmospheric carbon particles in Los Angeles. In: Wolff, G. T.; Klimisch, R. L., eds. *Particulate carbon: atmospheric life cycle*. New York, NY: Plenum Press; pp. 207-243.
- Cawse, P. A. (1981) Trace elements in the atmosphere of the United Kingdom. Presented at: ESNA meeting; September-October; Aberdeen, Scotland.
- Chamberlain, A. C. (1983) Deposition and resuspension. In: Pruppacher, H. R.; Semonin, R. G.; Slinn, W. G. N., eds. *Precipitation scavenging, dry deposition, and resuspension, v. 2: dry deposition and resuspension: proceedings of the fourth international conference; November-December 1982; Santa Monica, CA*. New York, NY: Elsevier; pp. 731-751.
- Chameides, W. L. (1984) The photochemistry of a remote marine stratiform cloud. *J. Geophys. Res.* [Atmos.] 89: 4739-4755.
- Chameides, W. L.; Davis, D. D. (1982) The free radical chemistry of cloud droplets and its impact upon the composition of rain. *J. Geophys. Res. C: Oceans Atmos.* 87: 4863-4877.
- Chan, W. H.; Tang A. J. S.; Chung, D. H. S.; Lusi, M. A. (1986) Concentration and deposition of trace metals in Ontario - 1982. *Water Air Soil Pollut.* 29: 373-389.
- Chan, C. K.; Flagan, R. C.; Seinfeld, J. H. (1992) Water activities of $\text{NH}_4\text{NO}_3/(\text{NH}_4)_2\text{SO}_4$ solutions. *Atmos. Environ.* Part A 26: 1661-1673.
- Chang, S. G.; Brodzinsky, R.; Gundel, L. A.; Novakov, T. (1982) Chemical and catalytic properties of elemental carbon. In: Wolff, G. T.; Klimisch, R. L., eds. *Particulate carbon: atmospheric life cycle*. New York, NY: Plenum Press; pp. 158-181.

- Chang, J. S.; Middleton, P. B.; Stockwell, W. R.; Walcek, C. J.; Pleim, J. E.; Lansford, H. H.; Madronich, S.; Binkowski, F. S.; Seaman, N. L.; Stauffer, D. R. (1991) The regional acid deposition model and engineering model. In: Irving, P. M., ed. *Acidic deposition: state of science and technology, volume I: emissions, atmospheric processes, and deposition*. Washington, DC: The U.S. National Acid Precipitation Assessment Program. (State of science and technology report no. 4).
- Chapman, E. G.; Luecken, D. J.; Dana, M. T.; Easter, R. C.; Hales, J. M.; Laulainen, N. S.; Thorp, J. M. (1987) Inter-storm comparisons from the OSCAR high-density network experiment. *Atmos. Environ.* 21: 531-549.
- Cheng, Y.-S.; Carpenter, R. L.; Barr, E. B.; Hobbs, C. H. (1985) Size distribution of fine particle emissions from a steam plant with a fluidized-bed coal combustor. *Aerosol Sci. Technol.* 4: 175-189.
- Ching, J. K. S.; Alkezweeny, A. J. (1986) Tracer study of vertical exchange by cumulus clouds. *J. Clim. Appl. Meteorol.* 25: 1702-1711.
- Choularton, T. W.; Wicks, A. J.; Downer, R. M.; Gallagher, M. W.; Penkett, S. A.; Bandy, B. J.; Dollard, G. J.; Jones, B. M. R.; Davies, T. D.; Gay, M. J.; Tyler, B. J.; Fowler, D.; Cape, J. N.; Hargreaves, K. J. (1992) A field study of the generation of nitrate in a hill cap cloud. *Environ. Pollut.* 75: 69-73.
- Chow, J. C.; Watson, J. G.; Lowenthal, D. H.; Solomon, P. A.; Magliano, K. L.; Ziman, S. D.; Richards, L. W. (1992) PM₁₀ source apportionment in California's San Joaquin Valley. *Atmos. Environ. Part A* 26: 3335-3354.
- Chow, J. C.; Watson, J. G.; Pritchett, L. C.; Pierson, W. R.; Frazier, C. A.; Purcell, R. G. (1993a) The DRI thermal/optical reflectance carbon analysis system: description, evaluation and applications in U.S. air quality studies. In: Lodge, J. P., Jr. *Fourth international conference on carbonaceous particles in the atmosphere*; April 1991; Vienna, Austria. *Atmos. Environ. Part A* 27: 1185-1201.
- Chow, J. C.; Watson, J. G.; Lowenthal, D. H.; Solomon, P. A.; Magliano, K. L.; Ziman, S. D.; Richards, L. W. (1993b) PM₁₀ and PM_{2.5} compositions in California's San Joaquin Valley. *Aerosol Sci. Technol.* 18: 105-128.
- Chow, J. C.; Watson, J. G.; Fujita, E. M.; Lu, Z.; Lawson, D. R.; Ashbaugh, L. L. (1994) Temporal and spatial variations of PM_{2.5} and PM₁₀ aerosol in the Southern California Air Quality Study. *Atmos. Environ.* 28: 2061-2080.
- Chughtai, A. R.; Jassim, J. A.; Peterson, J. H.; Stedman, D. H.; Smith, D. M. (1991) Spectroscopic and solubility characteristics of oxidized soots. *Aerosol Sci. Technol.* 15: 112-126.
- Clark, T. L.; Cohn, R. D. (1990) The Across North America Tracer Experiment (ANATEX) model evaluation study. Research Triangle Park, NC: U.S. Environmental Protection Agency, Atmospheric Research and Exposure Assessment Laboratory; EPA report no. EPA/600/3-90/051. Available from: NTIS, Springfield, VA; PB90-261454.
- Clark, P. A.; Fletcher, I. S.; Kallend, A. S.; McElroy, W. J.; Marsh, A. R. W.; Webb, A. H. (1984) Observations of cloud chemistry during long-range transport of power plant plumes. *Atmos. Environ.* 18: 1849-1858.
- Clarke, A. D. (1989) Aerosol light absorption by soot in remote environments. *Aerosol Sci. Technol.* 10: 161-171.
- Clarke, A. D. (1992) Atmospheric nuclei in the remote free-troposphere. *J. Atmos. Chem.* 14: 479-488.
- Clarke, A. D. (1993) Atmospheric nuclei in the Pacific midtroposphere—their nature, concentration, and evolution. *J. Geophys. Res. [Atmos.]* 98: 20,633-20,647.
- Clarke, A. G.; Karani, G. N. (1992) Characterisation of the carbonate content of atmospheric aerosols. *J. Atmos. Chem.* 14: 119-128.

- Clarke, A. G.; Radojevic, M. (1987) Oxidation of SO₂ in rainwater and its role in acid rain chemistry. *Atmos. Environ.* 21: 1115-1123.
- Clarke, J. F.; Clark, T. L.; Ching, J. K. S.; Haagenson, P. L.; Husar, R. B.; Patterson, D. E. (1983) Assessment of model simulation of long-distance transport. *Atmos. Environ.* 17: 2449-2462.
- Clarke, A. D.; Weiss, R. E.; Charlson, R. J. (1984) Elemental carbon aerosols in the urban, rural and remote-marine troposphere and in the stratosphere: interferences from light absorption data and consequences regarding radiative transfer. *Sci. Total Environ.* 36: 97-102.
- Cobourn, W. G.; Husar, R. B.; Husar, J. D. (1978) Continuous *in situ* monitoring of ambient particulate sulfur using flame photometry and thermal analysis. In: Husar, R. B.; Lodge, J. P., Jr.; Moore, D. J., eds. *Sulfur in the atmosphere: proceedings of the international symposium; September 1977; Dubrovnik, Yugoslavia.* *Atmos. Environ.* 12: 89-98.
- Cocks, A. T.; McElroy, W. L.; Wallis, P. G. (1982) The oxidation of sodium sulphite solutions by hydrogen peroxide. Central Electricity Research Laboratories; report no. RD/L/2215N81.
- Cofer, W. R., III; Stevens, R. K.; Winstead, E. L.; Pinto, J. P.; Sebach, D. I.; Abdulraheem, M. Y.; Al-Sahafi, M.; Mazurek, M. A.; Rasmussen, R. A.; Cahoon, D. R.; Levine, J. S. (1992) Kuwaiti oil fires: compositions of source smoke. *J. Geophys. Res. [Atmos.]* 97: 14,521-14,525.
- Cohen, M. D.; Flagan, R. C.; Seinfeld, J. H. (1987a) Studies of concentrated electrolyte solutions using the electrodynamic balance. 1. Water activities for single-electrolyte solutions. *J. Phys. Chem.* 91: 4563-4574.
- Cohen, M. D.; Flagan, R. C.; Seinfeld, J. H. (1987b) Studies of concentrated electrolyte solutions using the electrodynamic balance. 2. Water activities for mixed-electrolyte solutions. *J. Phys. Chem.* 91: 4575-4582.
- Colbeck, I.; Appleby, L.; Hardman, E. J.; Harrison, R. M. (1990) The optical properties and morphology of cloud-processed carbonaceous smoke. *J. Aerosol Sci.* 21: 527-538.
- Collett, J. L., Jr.; Oberholzer, B.; Mosimann, L.; Staehelin, J.; Waldvogel, A. (1993a) Contributions of cloud processes to precipitation chemistry in mixed phase clouds. *Water Air Soil Pollut.* 68: 43-57.
- Collett, J., Jr.; Oberholzer, B.; Staehelin, J. (1993b) Cloud chemistry in Mt. Rigi Switzerland: dependence on drop size and relationship to precipitation chemistry. *Atmos. Environ. Part A* 27: 33-42.
- Colville, R. N.; Choularton, T. W.; Gallagher, M. W.; Wicks, A. J.; Downer, R. M.; Tyler, B. J.; Storeton-West, K. J.; Fowler, D.; Cape, J. N.; Dollard, G. J.; Davies, T. J.; Jones, B. M. R.; Penkett, S. A.; Bandy, B. J.; Burgess, R. A. (1994) Observation on Great Dun Fell of the pathways by which oxides of nitrogen are converted to nitrate. *Atmos. Environ.* 28: 397-408.
- Countess, R. J.; Wolff, G. T.; Cadle, S. H. (1980) The Denver winter aerosol: a comprehensive chemical characterization. *J. Air Pollut. Control Assoc.* 30: 1194-1200.
- Coutant, R. W.; Brown, L.; Chuang, J. C.; Riggan, R. M.; Lewis, R. G. (1988) Phase distribution and artifact formation in ambient air sampling for polynuclear aromatic hydrocarbons. *Atmos. Environ.* 22: 403-409.
- Coutant, R. W.; Callahan, P. J.; Chuang, J. C.; Lewis, R. G. (1992) Efficiency of silicone-grease-coated denuders for collection of polynuclear aromatic hydrocarbons. *Atmos. Environ. Part A* 26: 2831-2834.
- Covert, D. S.; Heintzenberg, J. (1984) Measurement of the degree of internal/external mixing of hygroscopic compounds and soot in atmospheric aerosols. *Sci. Total Environ.* 36: 347-352.

- Covert, D. S.; Charlson, R. J.; Ahlquist, N. C. (1972) A study of the relationship of chemical composition and humidity to light scattering by aerosols. *J. Appl. Meteorol.* 11: 968-976.
- Covert, D. S.; Heintzenberg, J.; Hansson, H.-C. (1990) Electro-optical detection of external mixtures in aerosols. *Aerosol Sci. Technol.* 12: 446-456.
- Covert, D. S.; Kapustin, V. N.; Quinn, P. K.; Bates, T. S. (1992) New particle formation in the marine boundary layer. *J. Geophys. Res. [Atmos.]* 97: 20,581-20,589.
- Cronn, D. R.; Charlson, R. J.; Knights, R. L.; Crittenden, A. L.; Appel, B. R. (1977) A survey of the molecular nature of primary and secondary components of particles in urban air by high-resolution mass spectrometry. *Atmos. Environ.* 11: 929-937.
- Currie, L. A.; Stafford, T. W.; Sheffield, A. E.; Klouda, G. A.; Wise, S. A.; Fletcher, R. A.; Donahue, D. J.; Jull, A. J. T.; Linick, T. W. (1989) Microchemical and molecular dating. *Radiocarbon* 31: 448-463.
- Currie, L. A.; Sheffield, A. E.; Riederer, C.; Gordon, G. E. (1994) Improved atmospheric understanding through exploratory data analysis and complementary modeling: the urban K-Pb-C system. *Atmos. Environ.* 28: 1359-1369.
- Daisey, J. M. (1987) Chemical composition of inhalable particulate matter—seasonal and intersite comparisons. In: Lioy, P. J.; Daisey, J. M., eds. *Toxic air pollution: a comprehensive study of non-criteria air pollutants*. Chelsea, MI: Lewis Publishers, Inc.; pp. 45-65.
- D'Almeida, G. A. (1989) Desert aerosol: characteristics and effects on climate. In: Leinen, M.; Sarnthein, M. *Paleoclimatology and paleometeorology: modern and past patterns of global atmospheric transport*. Boston, MA: Kluwer Academic Publishers; pp. 311-338. (NATO ASI series. Series C, mathematical and physical sciences: v. 282).
- Dana, M. T.; Drewes, D. R.; Glover, D. W.; Hales, J. M. (1976) *Precipitation scavenging of fossil-fuel effluents*. Research Triangle Park, NC: U.S. Environmental Protection Agency, Environmental Sciences Research Laboratory; report no. EPA-600/4-76-031. Available from: NTIS, Springfield, VA; PB-256649.
- Danielsen, E. F. (1961) Trajectories: isobaric, isentropic and actual. *J. Meteorol.* 18: 479-486.
- Dasch, J. M.; Cadle, S. H. (1989) Atmospheric carbon particles in the Detroit urban area: wintertime sources and sinks. *Aerosol Sci. Technol.* 10: 236-248.
- Daum, P. H. (1988) Processes determining cloudwater composition: inferences from field measurements. In: Unsworth, M. H.; Fowler, D., eds. *Acid deposition at high elevation sites*. Dordrecht, The Netherlands: Kluwer; pp. 139-153.
- Daum, P. H.; Kelly, T. J.; Schwartz, S. E.; Newman, L. (1984a) Measurements of the chemical composition of stratiform clouds. *Atmos. Environ.* 18: 2671-2684.
- Daum, P. H.; Schwartz, S. E.; Newman, L. (1984b) Acidic and related constituents in liquid water stratiform clouds. *J. Geophys. Res. [Atmos.]* 89: 1447-1458.
- Daum, P. H.; Kelly, T. J.; Strapp, J. W.; Leaitch, W. R.; Joe, P.; Schemenauer, R. S.; Isaac, G. A.; Anlauf, K. G.; Wiebe, H. A. (1987) Chemistry and physics of a winter stratus cloud layer: a case study. *J. Geophys. Res. [Atmos.]* 92: 8426-8436.
- Daum, P. H.; Kleinman, L. I.; Hills, A. J.; Lazrus, A. L.; Leslie, A. C. D.; Busness, K.; Boatman, J. (1990) Measurement and interpretation of concentrations of H₂O₂ and related species in the upper midwest during summer. *J. Geophys. Res. [Atmos.]* 95: 9857-9871.

- Daum, P. H.; Al-Sunaid, A.; Busness, K. M.; Hales, J. M.; Mazurek, M. (1993) Studies of the Kuwait oil fire plume during midsummer 1991. *J. Geophys. Res. [Atmos.]* 98: 16,809-16,827.
- Däumer, B.; Niessner, R.; Klockow, D. (1992) Laboratory studies of the influence of thin organic films on the neutralization reaction of H₂SO₄ aerosol with ammonia. *J. Aerosol Sci.* 23: 315-325.
- Davidson, C. I.; Wu, Y.-L. (1990) Dry deposition of particles and vapors. In: Lindberg, S. E.; Page, A. L.; Norton, S. A., eds. *Acidic precipitation: v. 3, sources, deposition, and canopy interactions*. New York, NY: Springer-Verlag; pp. 103-216.
- De Bock, L. A.; Van Malderen, H.; Van Grieken, R. E. (1994) Individual aerosol particle composition variations in air masses crossing the North Sea. *Environ. Sci. Technol.* 28: 1513-1520.
- Delumyea, R. D.; Kalivretenos, A. (1987) Elemental carbon and lead content of fine particles from American and French cities of comparable size and industry, 1985. *Atmos. Environ.* 21: 1643-1647.
- Dennis, R. L.; McHenry, J. N.; Barchet, W. R.; Binkowski, F. S.; Byun, D. W. (1993) Correcting RADM's sulfate underprediction: discovery and correction of model errors and testing the corrections through comparisons against field data. *Atmos. Environ. Part A* 27: 975-997.
- De Raat, W. K.; Bakker, G. L.; de Meijere, F. A. (1990) Comparison of filter materials used for sampling of mutagens and polycyclic aromatic hydrocarbons in ambient airborne particles. *Atmos. Environ. Part A* 24: 2875-2887.
- De Santis, F.; Allegrini, I. (1992) Heterogeneous reactions of SO₂ and NO₂ on carbonaceous surfaces. *Atmos. Environ. Part A* 26: 3061-3064.
- De Valk, J. P. J. M. M. (1994) A model for cloud chemistry: a comparison between model simulations and observations in stratus and cumulus. *Atmos. Environ.* 28: 1665-1678.
- Dickerson, R. R.; Huffman, G. J.; Luke, W. T.; Nunnermacker, L. J.; Pickering, K. E.; Leslie, A. C. D.; Lindsey, C. G.; Slinn, W. G. N.; Kelly, T. J.; Daum, P. H.; Delany, A. C.; Greenberg, J. P.; Zimmerman, P. R.; Boatman, J. F.; Ray, J. D.; Stedman, D. H. (1987) Thunderstorms: an important mechanism in the transport of air pollutants. *Science (Washington, DC)* 235: 460-465.
- Dittenhoefer, A. C.; de Pena, R. G. (1978) A study of production and growth of sulfate particles in plumes from a coal-fired power plant. *Atmos. Environ.* 12: 297-306.
- Dlugi, R. (1989) Chemistry and deposition of soot particles in moist air and fog. *Aerosol Sci. Technol.* 10: 93-105.
- Dlugi, R.; Güsten, H. (1983) The catalytic and photocatalytic activity of coal fly ashes. *Atmos. Environ.* 17: 1765-1771.
- Dod, R. L.; Brown, N. J.; Mowrer, F. W.; Novakov, T.; Williamson, R. B. (1989) Smoke emission factors from medium-scale fires: part 2. *Aerosol Sci. Technol.* 10: 20-27.
- Doyle, G. J.; Tuazon, E. C.; Graham, R. A.; Mischke, T. M.; Winer, A. M.; Pitts, J. N., Jr. (1979) Simultaneous concentrations of ammonia and nitric acid in a polluted atmosphere and their equilibrium relationship to particulate ammonium nitrate. *Environ. Sci. Technol.* 13: 1416-1419.
- Draxler, R. R. (1982) Measuring and modeling the transport and dispersion of Krypton-85 1500 km from a point source. *Atmos. Environ.* 16: 2763-2776.
- Draxler, R. R. (1984) Diffusion and transport experiments. In: Randerson, D., ed. *Atmospheric science and power production*. Washington, DC: U.S. Department of Energy, Office of Scientific and Technical Information; pp. 367-422; report no. DOE/TIC-27601. Available from: NTIS, Springfield, VA; DE84-005177.

- Draxler, R. R.; Dietz, R.; Lagomarsino, R. J.; Start, G. (1991) Across North America Tracer Experiment (ANATEX): sampling and analysis. *Atmos. Environ. Part A* 25: 2815-2836.
- Drewes, D. R.; Hales, J. M. (1982) SMICK—a scavenging model incorporating chemical kinetics. *Atmos. Environ.* 16: 1717-1724.
- Duce, R. A.; Mohnen, V. A.; Zimmerman, P. R.; Grosjean, D.; Cautreels, W.; Chatfield, R.; Jaenicke, R.; Ogren, J. A.; Pellizzari, E. D.; Wallace, G. T. (1983) Organic material in the global troposphere. *Rev. Geophys. Space Phys.* 21: 921-952.
- Durham, J. L.; Wilson, W. E.; Ellestad, T. G.; Willeke, K.; Whitby, K. T. (1975) Comparison of volume and mass distributions for Denver aerosols. *Atmos. Environ.* 9: 717-722.
- Dzubay, T. G.; Stevens, R. K.; Gordon, G. E.; Olmez, I.; Sheffield, A. E.; Courtney, W. J. (1988) A composite receptor method applied to Philadelphia aerosol. *Environ. Sci. Technol.* 22: 46-52.
- Eatough, D. J.; Richter, B. E.; Eatough, N. L.; Hansen, L. D. (1981) Sulfur chemistry in smelter and power plant plumes in the western U.S. In: White, W. H.; Moore, D. J.; Lodge, J. P., Jr., eds. *Plumes and visibility: measurements and model components: proceedings of the symposium; November 1980; Grand Canyon National Park, AZ.* *Atmos. Environ.* 15: 2241-2253.
- Eatough, D. J.; Christensen, J. J.; Eatough, N. L.; Hill, M. W.; Major, T. D.; Mangelson, N. F.; Post, M. E.; Ryder, J. F.; Hansen, L. D.; Meisenheimer, R. G.; Fischer, J. W. (1982) Sulfur chemistry in a copper smelter plume. *Atmos. Environ.* 16: 1001-1015.
- Eatough, D. J.; Arthur, R. J.; Eatough, N. L.; Hill, M. W.; Mangelson, N. F.; Richter, B. E.; Hansen, L. D.; Cooper, J. A. (1984) Rapid conversion of SO₂(g) to sulfate in a fog bank. *Environ. Sci. Technol.* 18: 855-859.
- Eatough, D. J.; Sedar, B.; Lewis, L.; Hansen, L. D.; Lewis, E. A.; Farber, R. J. (1989) Determination of semivolatile organic compounds in particles in the Grand Canyon area. *Aerosol Sci. Technol.* 10: 438-449.
- Eatough, D. J.; Wadsworth, A.; Eatough, D. A.; Crawford, J. W.; Hansen, L. D.; Lewis, E. A. (1993) A multiple-system, multi-channel diffusion denuder sampler for the determination of fine-particulate organic material in the atmosphere. *Atmos. Environ. Part A* 27: 1213-1219.

- Eatough, D. J.; Tang, H.; Cui, W.; Machir, J. (1995) Determination of the size distribution and chemical composition of fine particulate semi-volatile organic material in urban environments using diffusion denuder technology. In: Phalen, R. F.; Bates, D. V., eds. Proceedings of the colloquium on particulate air pollution and human mortality and morbidity, part II; Janaury 1994; Irvine, CA. *Inhalation Toxicol.* 7: 691-710.
- Eisele, F. L.; Bradshaw, J. D. (1993) The elusive hydroxyl radical: measuring OH in the atmosphere. *Anal. Chem.* 65: 927A-939A.
- Eisele, F. L.; Tanner, D. J. (1993) Measurement of the gas phase concentration of H₂SO₄ and methane sulfonic acid and estimates of H₂SO₄ production and loss in the atmosphere. *J. Geophys. Res. [Atmos.]* 98: 9001-9010.
- Eldering, A.; Cass, G. R.; Moon, K. C. (1994) An air monitoring network using continuous particle size distribution monitors: connecting pollutant properties to visibility via Mie scattering calculations. *Atmos. Environ.* 28: 2733-2749.
- Eldred, R. A.; Cahill, T. A.; Flocchini, R. G. (1994) Comparison of PM₁₀ and PM_{2.5} aerosols in the IMPROVE network. In: Proceedings of an international specialty conference on aerosol and atmospheric optics: radiative balance and visual air quality, volume A. Pittsburgh, PA: Air and Waste Management Association. Air Waste: submitted.
- Eltgroth, M. W.; Hobbs, P. V. (1979) Evolution of particles in the plumes of coal-fired power plants—II. A numerical model and comparisons with field measurements. *Atmos. Environ.* 13: 953-975.
- Er-El, J.; Peskin, R. L. (1981) Relative diffusion of constant-level balloons in the southern hemisphere. *J. Atmos. Sci.* 38: 2264-2274.
- Erickson, R. E.; Yates, L. M.; Clark, R. L.; McEwen, D. (1977) The reaction of sulfur dioxide with ozone in water and its possible atmospheric significance. *Atmos. Environ.* 11: 813-817.
- Facchini, M. C.; Fuzzi, S.; Lind, J. A.; Fierlinger-Oberlinninger, H.; Kalina, M.; Puxbaum, H.; Winiwarter, W.; Arends, B. G.; Wobrock, W.; Jaeschke, W.; Berner, A.; Kruisz, C. (1992) Phase-partitioning and chemical reactions of low molecular weight organic compounds in fog. *Tellus Ser. B* 44B: 533-544.
- Falerios, M.; Schild, K.; Sheehan, P.; Paustenbach, D. (1992) Airborne concentrations of trivalent and hexavalent chromium from contaminated soils at unpaved partially paved commercial/industrial sites. *J. Air Waste Manage. Assoc.* 42: 40-48.
- Ferber, G. J.; Telegadas, K.; Heffter, J. L.; Dickson, C. R.; Dietz, R. N.; Krey, P. W. (1981) Demonstration of a long-range atmospheric tracer system using perfluorocarbons. Silver Springs, MD: National Oceanic and Atmospheric Administration; NOAA report no. NOAA TM ERL ARL-101.
- Ferber, G. J.; Heffter, J. L.; Draxler, R. R.; Lagomarsino, R. J.; Thomas, F. L.; Dietz, R. N.; Benkovitz, C. M. (1986) Cross-Appalachian Tracer Experiment (CAPTEX-83) final report. Silver Springs, MD: National Oceanic and Atmospheric Administration; NOAA report no. NOAA TM ERL ARL-142.
- Fernandez de la Mora, J. (1986) Inertia and interception in the deposition of particles from boundary layers. *Aerosol Sci. Technol.* 5: 261-266.
- Fernandez de la Mora, J.; Friedlander, S. K. (1982) Aerosol and gas deposition to fully rough surfaces: filtration model for blade-shaped elements. *Int. J. Heat Mass Transfer* 25: 1725-1735.
- Finlayson-Pitts, B. J.; Pitts, J. N., Jr. (1986) *Atmospheric chemistry: fundamentals and experimental techniques*. New York, NY: John Wiley & Sons; pp. 783-1007.

- Fitzgerald, J. W. (1973) Dependence of the supersaturation spectrum of CCN on aerosol size distribution and composition. Presented at: the second international workshop on condensation and ice nuclei; August 1970; Fort Collins, CO. *J. Atmos. Sci.* 30: 628-634.
- Fitzgerald, J. W.; Hoppel, W. A.; Vietti, M. A. (1982) The size and scattering coefficient of urban aerosol particles at Washington, DC as a function of relative humidity. *J. Atmos. Sci.* 39: 1838-1852.
- Flossmann, A. I.; Hall, W. D.; Pruppacher, H. R. (1985) A theoretical study of the wet removal of atmospheric pollutants. Part I: The redistribution of aerosol particles captured through nucleation and impaction scavenging by growing cloud drops. *J. Atmos. Sci.* 42: 583-606.
- Foitzik, L. (1950) Zur meteorologischen Optik von Dunst und Nebel: Teil II [The meteorological optics of haze and fog: part II]. *Z. Meteorol.* 4: 321-329.
- Foreman, W. T.; Bidleman, T. F. (1990) Semivolatile organic compounds in the ambient air of Denver, Colorado. *Atmos. Environ. Part A* 24: 2405-2416.
- Forkel, R.; Seidl, W.; Dlugi, R.; Deigele, E. (1990) A one-dimensional numerical model to simulate formation and balance of sulfate during radiation fog events. *J. Geophys. Res. [Atmos.]* 95: 18,501-18,515.
- Forrest, J.; Newman, L. (1973) Sampling and analysis of atmospheric sulfur compounds for isotope ratio studies. *Atmos. Environ.* 7: 561-573.
- Forrest, J.; Newman, L. (1977a) Further studies on the oxidation of sulfur dioxide in coal-fired power plant plumes. *Atmos. Environ.* 11: 465-474.
- Forrest, J.; Newman, L. (1977b) Oxidation of sulfur dioxide in the Sudbury smelter plume. *Atmos. Environ.* 11: 517-520.
- Forrest, J.; Garber, R.; Newman, L. (1979) Formation of sulfate, ammonium and nitrate in an oil-fired power plant plume. *Atmos. Environ.* 13: 1287-1297.
- Forrest, J.; Garber, R. W.; Newman, L. (1981) Conversion rates in power plant plumes based on filter pack data: the coal-fired Cumberland plume. *Atmos. Environ.* 15: 2273-2282.
- Freeman, D. J.; Cattell, F. C. R. (1990) Woodburning as a source of atmospheric polycyclic aromatic hydrocarbons. *Environ. Sci. Technol.* 24: 1581-1585.
- Frick, G. M.; Hoppel, W. A. (1993) Airship measurements of aerosol size distributions, cloud droplet spectra, and trace gas concentrations in the marine boundary layer. *Bull. Am. Meteorol. Soc.* 74: 2195-2202.
- Fried, A.; Henry, B. E.; Calvert, J. G.; Mozurkewich, M. (1994) The reaction probability of N_2O_5 with sulfuric acid aerosols at stratospheric temperatures and compositions. *J. Geophys. Res. [Atmos.]* 99: 3517-3532.
- Friedlander, S. K. (1970) The characterization of aerosols distributed with respect to size and chemical composition. *J. Aerosol Sci.* 1: 295-307.
- Friedlander, S. K.; Turner, J. R.; Hering, S. V. (1986) A new method for estimating dry deposition velocities for atmospheric aerosols. *J. Aerosol Sci.* 17: 240-244.
- Fung, C. S.; Misra, P. K.; Bloxam, R.; Wong, S. (1991) A numerical experiment on the relative importance of H_2O_2 and O_3 in aqueous conversion of SO_2 to SO_4^{2-} . *Atmos. Environ. Part A* 25: 411-423.
- Fuzzi, S.; Castillo, R. A.; Justo, J. E.; Lala, G. G. (1984) Chemical composition of radiation fog water at Albany, New York, and its relationship to fog microphysics. *J. Geophys. Res. [Atmos.]* 89: 7159-7164.

- Fuzzi, S.; Orsi, G.; Nardini, G.; Facchini, M. C.; McLaren, S.; McLaren, E.; Mariotti, M. (1988) Heterogeneous processes in the Po Valley radiation fog. *J. Geophys. Res. [Atmos.]* 93: 11,141-11,151.
- Gagosian, R. B.; Peltzer, E. T.; Merrill, J. T. (1987) Long-range transport of terrestrially derived lipids in aerosols from the south Pacific. *Nature (London)* 325: 800-803.
- Galloway, J. N.; Thornton, J. D.; Norton, S. A.; Volchok, H. L.; McLean, R. A. N. (1982) Trace metals in atmospheric deposition: a review and assessment. *Atmos. Environ.* 16: 1677-1700.
- Garland, J. A. (1979) Resuspension of particulate matter from grass and soil. Harwell, United Kingdom: Atomic Energy Research Establishment; report no. AERE-R9452. Available from: NTIS, Springfield, VA.; AERE-R9452.
- Gatz, D. F. (1977) Scavenging ratio measurements in METROMEX. In: Semonin, R. G.; Beadle, R. W., eds. *Precipitation scavenging (1974): proceedings of a symposium; October 1974; Champaign, IL.* Oak Ridge, TN: Energy Research and Development Administration; pp. 71-87. Available from: NTIS, Springfield, VA; CONF-741003. (ERDA symposium series no. 41).
- Gebhart, K. A.; Malm, W. C.; Day, D. (1994) Examination of the effects of sulfate acidity and relative humidity on light scattering at Shenandoah National Park. *Atmos. Environ.* 28: 841-849.
- Gerde, P.; Scholander, P. (1989) Mass transfer rates of polycyclic aromatic hydrocarbons between micron-size particles and their environment—theoretical estimates. *Environ. Health Perspect.* 79: 249-258.
- Germani, M. S.; Buseck, P. R. (1991) Automated scanning electron microscopy for atmospheric particle analysis. *Anal. Chem.* 63: 2232-2237.
- Gervat, G. P.; Clark, P. A.; Marsh, A. R. W.; Choularton, T. W.; Gay, M. J. (1988) Controlled chemical kinetic experiments in cloud: a review of the CERL/UMIST Great Dun Fell project. In: Unsworth, M. H.; Fowler, D., eds. *Acid deposition at high elevation sites: proceedings of the NATO advanced research workshop; September 1986; Edinburgh, United Kingdom.* Dordrecht, The Netherlands: Kluwer Academic Publishers; pp. 283-298. (NATO ASI series C: mathematical and physical sciences v. 252).
- Gery, M. W.; Fox, D. L.; Jeffries, H. E.; Stockburger, L.; Weathers, W. S. (1985) A continuous stirred tank reactor investigation of the gas-phase reaction of hydroxyl radicals and toluene. *Int. J. Chem. Kinet.* 17: 931-955.
- Gery, M. W.; Fox, D. L.; Kamens, R. M.; Stockburger, L. (1987) Investigation of hydroxyl radical reactions with o-xylene and m-xylene in a continuous stirred tank reactor. *Environ. Sci. Technol.* 21: 339-348.
- Ghan, S. J.; Chuang, C. C.; Penner, J. E. (1993) A parameterization of cloud droplet nucleation, part I: single aerosol type. *Atmos. Res.* 30: 198-221.
- Gifford, F. A., Jr. (1961) Use of routine meteorological observations for estimating atmospheric dispersion. *Nucl. Saf.* 2: 47-51.
- Gill, P. S.; Graedel, T. E.; Wechsler, C. J. (1983) Organic films on atmospheric aerosol particles, fog droplets, cloud droplets, raindrops and snowflakes. *Rev. Geophys. Space Phys.* 21: 903-920.
- Gillani, N. V. (1985) Modeling of chemical transformations of SO_x and NO_x in the polluted atmosphere—an overview of approaches and current status. In: De Wispelaere, C., ed. *Air pollution modeling and its application IV.* New York, NY: Plenum Publishers; pp. 163-192.
- Gillani, N. V. (1986) Ozone formation in pollutant plumes: a reactive plume model with arbitrary crosswind resolution. Research Triangle Park, NC: U.S. Environmental Protection Agency, Atmospheric Sciences Research Laboratory; EPA report no. EPA/600/3-86/051. Available from: NTIS, Springfield, VA; PB86-236973.

- Gillani, N. V.; Husar, R. B. (1976) Synoptic-scale haziness over the eastern US and its long range transport. Presented at: 4th National AMS/SAF conference on fire and forest meteorology; Boston, MA.
- Gillani, N. V.; Pleim, J. E. (1995) Subgrid-scale features of anthropogenic emissions of VOC and NO_x in the context of regional Eulerian models. *Atmos. Environ.*: in press.
- Gillani, N. V.; Wilson, W. E. (1980) Formation and transport of ozone and aerosols in power plant plumes. *Ann. N. Y. Acad. Sci.* 338: 276-296.
- Gillani, N. V.; Wilson, W. E. (1983) Gas-to-particle conversion of sulfur in power plant plumes—II. observations of liquid-phase conversions. *Atmos. Environ.* 17: 1739-1752.
- Gillani, N. V.; Husar, R. B.; Husar, J. D.; Patterson, D. E.; Wilson, W. E., Jr. (1978) Project MISTT: kinetics of particulate sulfur formation in a power plant plume out to 300 km. *Atmos. Environ.* 12: 589-598.
- Gillani, N. V.; Kohli, S.; Wilson, W. E. (1981) Gas-to-particle conversion of sulfur in power plant plumes—I. parametrization of the conversion rate for dry, moderately polluted ambient conditions. *Atmos. Environ.* 15: 2293-2313.
- Gillani, N. V.; Colby, J. A.; Wilson, W. E. (1983) Gas-to-particle conversion of sulfur in power plant plumes—III. parameterization of plume-cloud interactions. *Atmos. Environ.* 17: 1753-1763.
- Gillani, N. V.; Shannon, J. D.; Patterson, D. E. (1984) Transport processes. In: Altshuller, A. P.; Linthurst, R. A., eds. *The acidic deposition phenomenon and its effects: critical assessment review papers, v. 1: atmospheric sciences*. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development; report no. EPA/600/8-83/016AF. Available from: NTIS, Springfield, VA; PB85-100030.
- Gillani, N. V.; Schwartz, S. E.; Leitch, W. R.; Strapp, J. W.; Isaac, G. A. (1995) Field observations in continental stratiform clouds: partitioning of cloud particles between droplets and unactivated interstitial aerosols. *J. Geophys. Res. [Atmos.]* 100: 18,687-18,706.
- Gillette, D. A. (1974) On the production of soil wind erosion aerosols having the potential for long range transport. *J. Rech. Atmos.* 8: 735-744.
- Gillette, D. (1980) Major contributions of natural primary continental aerosols: source mechanisms. In: Kniép, T. J.; Lioy, P. J., eds. *Aerosols: anthropogenic and natural, sources and transport*. Ann N. Y. Acad. Sci. 338: 348-358.
- Gillette, D. A.; Hanson, K. J. (1989) Spatial and temporal variability of dust production caused by wind erosion in the United States. *J. Geophys. Res. [Atmos.]* 94: 2197-2206.
- Gillette, D.; Nagamoto, C. (1992) [Size distribution and single particle composition for two dust storms in Soviet Central Asia in September 1989 and size distributions and chemical composition of local soil]. In: Golitsyn, G., ed. *Soviet-American experiment for the investigation of arid aerosols*. St. Petersburg, USSR: Typhoon; pp. 130-140.
- Gillette, D. A.; Passi, R. (1988) Modeling dust emission caused by wind erosion. *J. Geophys. Res. [Atmos.]* 93: 14,233-14,242.
- Gillette, D. A.; Sinclair, P. C. (1990) Estimation of suspension of alkaline material by dust devils in the United States. *Atmos. Environ. Part A* 24: 1135-1142.
- Gillette, D. A.; Walker, T. R. (1977) Characteristics of airborne particles produced by wind erosion of sandy soil, high plains of west Texas. *Soil Sci.* 123: 97-110.

- Gillette, D. A.; Clayton, R. N.; Mayeda, T. K.; Jackson, M. L.; Sridhar, K. (1978) Tropospheric aerosols from some major dust storms of the southwestern United States. *J. Appl. Meteorol.* 17: 832-845.
- Gillette, D. A.; Stensland, G. J.; Williams, A. L.; Barnard, W.; Gatz, D.; Sinclair, P. C.; Johnson, T. C. (1992) Emissions of alkaline elements calcium, magnesium, potassium, and sodium from open sources in the contiguous United States. *Global Biogeochem. Cycles* 6: 437-457.
- Gleason, J. F.; Sinha, A.; Howard, C. J. (1987) Kinetics of the gas-phase reaction $\text{HOSO}_2 + \text{O}_2 \rightarrow \text{HO}_2 + \text{SO}_3$. *J. Phys. Chem.* 91: 719-724.
- Godish, T. (1985) *Air quality*. Chelsea, MI: Lewis Publishers, Inc.
- Godowitch, J. M. (1989) Evaluation and sensitivity analyses results of the MESOPUFF II model with CAPTEX measurements. Research Triangle Park, NC: U.S. Environmental Protection Agency, Atmospheric Research and Exposure Assessment Laboratory; EPA report no. EPA/600/3-89/056. Available from: NTIS, Springfield, VA; PB89-198253.
- Goldberg, E. D. (1985) *Black carbon in the environment: properties and distribution*. New York, NY: John Wiley & Sons. (Metcalf, R. L.; Stumm, W., eds. *Environmental science and technology series*).
- Gordon, G. E. (1991) Airborne particles on global and regional scales. *Environ. Sci. Technol.* 25: 1822-1828.
- Gordon, R. J.; Trivedi, N. J.; Singh, B. P.; Ellis, E. C. (1988) Characterization of aerosol organics by diffuse reflectance Fourier transform infrared spectroscopy. *Environ. Sci. Technol.* 22: 672-677.
- Goschnick, J.; Fichtner, M.; Lipp, M.; Schuricht, J.; Ache, H. J. (1993) Depth-resolved chemical analysis of environmental microparticles by secondary mass spectrometry. *Appl. Surf. Sci.* 70/71: 63-67.
- Graedel, T. E.; Goldberg, K. I. (1983) Kinetic studies of raindrop chemistry: 1. inorganic and organic processes. *J. Geophys. Res. C: Oceans Atmos.* 88: 10,865-10,882.
- Graedel, T. E.; Weschler, C. J. (1981) Chemistry within aqueous atmospheric aerosols and raindrops. *Rev. Geophys. Space Phys.* 19: 505-539.
- Graedel, T. E.; Hawkins, D. T.; Claxton, L. D. (1986) *Atmospheric chemical compounds: sources, occurrence, and bioassay*. Orlando, FL: Academic Press, Inc.
- Granat, L.; Soderland, R. (1975) *Atmospheric deposition due to long and short distance sources with special reference to wet and dry deposition of sulfur*. Stockholm, Sweden: Stockholm University, Meteorological Institute; report no. MISU-A32.
- Gray, H. A. (1986) Control of atmospheric fine primary carbon particle concentration [Ph.D. thesis]. Pasadena, CA: California Institute of Technology; EQL report no. 23.
- Gray, H. A.; Cass, G. R.; Huntzicker, J. J.; Heyerdahl, E. K.; Rau, J. A. (1984) Elemental and organic carbon particle concentrations: a long-term perspective. *Sci. Total Environ.* 36: 17-25.
- Gray, H. A.; Cass, G. R.; Huntzicker, J. J.; Heyerdahl, E. K.; Rau, J. A. (1986) Characteristics of atmospheric organic and elemental carbon particle concentrations in Los Angeles. *Environ. Sci. Technol.* 20: 580-589.
- Grell, G. A.; Dudhia, J.; Stauffer, D. R. (1994) A description of the fifth-generation Penn State/NCAR mesoscale model (MM5). Boulder, CO: National Center for Atmospheric Research; technical note no. NCAR/TN-398+STR.
- Grosjean, D. (1977) Aerosols. In: *Ozone and other photochemical oxidants*. Washington, DC: National Academy of Sciences; pp. 45-125.

- Grosjean, D. (1984a) Particulate carbon in Los Angeles air. *Sci. Total Environ.* 32: 133-145.
- Grosjean, D. (1984b) Photooxidation of 1-heptane. *Sci. Total Environ.* 37: 195-211.
- Grosjean, D. (1985) Reactions of *o*-cresol and nitrocresol with NO_x in sunlight and with ozone-nitrogen dioxide mixtures in the dark. *Environ. Sci. Technol.* 19: 968-974.
- Grosjean, D. (1992) *In situ* organic aerosol formation during a smog episode: estimated production and chemical functionality. *Atmos. Environ. Part A* 26: 953-963.
- Grosjean, D.; Friedlander, S. K. (1975) Gas-particle distribution factors for organic and other pollutants in the Los Angeles atmosphere. *J. Air Pollut. Control Assoc.* 25: 1038-1044.
- Grosjean, D.; Seinfeld, J. H. (1989) Parameterization of the formation potential of secondary organic aerosols. *Atmos. Environ.* 23: 1733-1747.
- Gundel, L. A.; Guyot-Sionnest, N. S.; Novakov, T. (1989) A study of the interaction of NO₂ with carbon particles. *Aerosol Sci. Technol.* 10: 343-351.
- Gundel, L. A.; Lee, V. C.; Mahanama, K. R. R.; Stevens, R. K.; Daisey, J. M. (1995) Direct determination of the phase distributions of semi-volatile polycyclic aromatic hydrocarbons using annular denuders. *Atmos. Environ.* 29: 1719-1733.
- Hahn, J. (1980) Organic constituents of natural aerosols. *Ann. N. Y. Acad. Sci.* 338: 359-376.
- Hales, J. M. (1991) Atmospheric processes research and process model development. Section 4. Precipitation scavenging. In: Irving, P. M., ed. *Acidic deposition: state of science and technology, volume I: emissions, atmospheric processes, and deposition*. Washington, DC: The U.S. National Acid Precipitation Assessment Program; pp. 2-109 - 2-168. (State of science and technology report no. 2).
- Hales, J. M.; Dana, M. T. (1979) Precipitation scavenging of urban pollutants by convective storm systems. *J. Appl. Meteorol.* 18: 294-316.
- Hales, J. M.; Hicks, B. B.; Miller, J. M. (1987) The role of research measurement networks as contributors to federal assessments of acid deposition. *Bull. Am. Meteorol. Soc.* 68: 216-225.
- Hall, F. P., Jr.; Duchon, C. E.; Lee, L. G.; Hagan, R. R. (1973) Long-range transport of air pollution: a case study, August 1970. *Mon. Weather Rev.* 101: 404-411.
- Hamilton, R. S.; Mansfield, T. A. (1991) Airborne particulate elemental carbon: its sources, transport and contribution to dark smoke and soiling. *Atmos. Environ. Part A* 25: 715-723.
- Hampton, C. V.; Pierson, W. R.; Schuetzle, D.; Harvey, T. M. (1983) Hydrocarbon gases emitted from vehicles on the road. 2. Determination of emission rates from diesel and spark-ignition vehicles. *Environ. Sci. Technol.* 17: 699-708.
- Hänel, G. (1976) The properties of atmospheric aerosol particles as functions of the relative humidity at thermodynamic equilibrium with the surrounding moist air. In: Landsberg, H. E.; Van Mieghem, J., eds. *Advances in geophysics*: v. 19. New York, NY: Academic Press; pp. 73-188.
- Hansen, A. D. A.; Novakov, T. (1989) Real-time measurements of the size fractionation of ambient black carbon aerosols at elevated humidities. *Aerosol Sci. Technol.* 10: 106-110.
- Hansen, A. D. A.; Rosen, H. (1990) Individual measurements of the emission factor of aerosol black carbon in automobile plumes. *J. Air Waste Manage. Assoc.* 40: 1654-1657.

- Hansen, A. D. A.; Benner, W. H.; Novakov, T. (1991) Sulfur dioxide oxidation in laboratory clouds. *Atmos. Environ. Part A* 25: 2521-2530.
- Harrison, L. (1985) The segregation of aerosols by cloud-nucleating activity. Part II: Observation of an urban aerosol. *J. Clim. Appl. Meteorol.* 24: 312-321.
- Harrison, R. M.; Kitto, A.-M. N. (1992) Estimation of the rate constant for the reaction of acid sulphate aerosol with NH_3 gas from atmospheric measurements. *J. Atmos. Chem.* 15: 133-143.
- Harrison, R. M.; Msibi, I. M. (1994) Validation of techniques for fast response measurement of HNO_3 and NH_3 and determination of the $[\text{NH}_3][\text{HNO}_3]$ concentration product. *Atmos. Environ.* 28: 247-255.
- Harrison, R. M.; Pio, C. A. (1983) A comparative study of the ionic composition of rainwater and atmospheric aerosols: implications for the mechanism of acidification of rainwater. *Atmos. Environ.* 17: 2539-2543.
- Harrison, R. M.; Laxen, D. P. H.; Wilson, S. J. (1981) Chemical associations of lead, cadmium, copper, and zinc in street dusts and roadside soils. *Environ. Sci. Technol.* 15: 1378-1383.
- Hart, K. M.; Pankow, J. F. (1994) High-volume air sampler for particle and gas sampling. 2. Use of backup filters to correct for the adsorption of gas-phase polycyclic aromatic hydrocarbons to the front filter. *Environ. Sci. Technol.* 28: 655-661.
- Hasan, H.; Dzubay, T. G. (1987) Size distributions of species in fine particles in Denver using a microorifice impactor. *Aerosol Sci. Technol.* 6: 29-39.
- Hatakeyama, S.; Tanonaka, T.; Weng, J.; Bandow, H.; Takagi, H.; Akimoto, H. (1985) Ozone-cyclohexene reaction in air: quantitative analysis of particulate products and the reaction mechanism. *Environ. Sci. Technol.* 19: 935-942.
- Hatakeyama, S.; Ohno, M.; Weng, J.; Takagi, H.; Akimoto, H. (1987) Mechanism for the formation of gaseous and particulate products from ozone-cycloalkene reactions in air. *Environ. Sci. Technol.* 21: 52-57.
- Hatakeyama, S.; Izumi, K.; Fukuyama, T.; Akimoto, H. (1989) Reactions of ozone with α -pinene and β -pinene in air: yields of gaseous and particulate products. *J. Geophys. Res. [Atmos.]* 94: 13,013-13,024.
- Hatakeyama, S.; Izumi, K.; Fukuyama, T.; Akimoto, H.; Washida, N. (1991) Reactions of OH with α -pinene and β -pinene in air: estimate of global CO production from the atmospheric oxidation of terpenes. *J. Geophys. Res. [Atmos.]* 96: 947-958.
- Hegg, D. A. (1985) The importance of liquid-phase oxidation of SO_2 in the troposphere. *J. Geophys. Res. [Atmos.]* 90: 3773-3779.
- Hegg, D. A.; Hobbs, P. V. (1979) Some observations of particulate nitrate concentrations in coal-fired power plant plumes. *Atmos. Environ.* 13: 1715-1716.
- Hegg, D. A.; Hobbs, P. V. (1980) Measurements of gas-to-particle conversion in the plumes from five coal-fired electric power plants. *Atmos. Environ.* 14: 99-116.
- Hegg, D. A.; Hobbs, P. V. (1982) Measurements of sulfate production in natural clouds. *Atmos. Environ.* 16: 2663-2668.
- Hegg, D. A.; Hobbs, P. V. (1983a) Errata [Hegg and Hobbs (1982)]. *Atmos. Environ.* 17: 1059.
- Hegg, D. A.; Hobbs, P. V. (1983b) Author's reply: measurements of sulfate production in natural clouds. *Atmos. Environ.* 17: 2632-2633.

- Hegg, D. A.; Hobbs, P. V. (1986) Sulfate and nitrate chemistry in cumuliform clouds. *Atmos. Environ.* 20: 901-909.
- Hegg, D. A.; Hobbs, P. V. (1987) Comparisons of measured sulfate production due to ozone oxidation in clouds with a kinetic rate equation. *Geophys. Res. Lett.* 14: 719-721.
- Hegg, D. A.; Hobbs, P. V. (1988) Comparisons of sulfate and nitrate production in clouds on the mid-Atlantic and Pacific Northwest Coasts of the United States. *J. Atmos. Chem.* 7: 325-333.
- Hegg, D. A.; Larson, T. V. (1990) The effects of microphysical parameterization on model predictions of sulfate production in clouds. *Tellus Ser. B* 42B: 272-284.
- Hegg, D. A.; Hobbs, P. V.; Radke, L. F. (1984) Measurements of the scavenging of sulfate and nitrate in clouds. *Atmos. Environ.* 18: 1939-1946.
- Hegg, D. A.; Radke, L. F.; Hobbs, P. V. (1990) Particle production associated with marine clouds. *J. Geophys. Res. [Atmos.]* 95: 13,917-13,926.
- Hegg, D. A.; Radke, L. F.; Hobbs, P. V. (1991) Measurements of Aitken nuclei and cloud condensation nuclei in the marine atmosphere and their relation to the DMS-cloud-climate hypothesis. *J. Geophys. Res. [Atmos.]* 96: 18,727-18,733.
- Hegg, D. A.; Yuen, P.-F.; Larson, T. V. (1992) Modeling the effects of heterogeneous cloud chemistry on the marine particle size distribution. *J. Geophys. Res. [Atmos.]* 97: 12,927-12,933.
- Heintzenberg, J.; Winkler, P. (1984) Elemental carbon in the urban aerosol: results of a seventeen month study in Hamburg, FRG. *Sci. Total Environ.* 36: 27-38.
- Heintzenberg, J.; Ogren, J. A.; Noone, K. J.; Gärdneus, L. (1989) The size distribution of submicrometer particles within and about stratocumulus cloud droplets on Mt. Åreskutan, Sweden. *Atmos. Res.* 24: 89-101.
- Heisler, S. L.; Friedlander, S. K. (1977) Gas-to-particle conversion in photochemical smog - aerosol growth laws and mechanisms for organics. *Atmos. Environ.* 11: 157-168.
- Hering, S. V.; Friedlander, S. K. (1982) Origins of aerosol sulfur size distributions in the Los Angeles basin. *Atmos. Environ.* 16: 2647-2656.
- Hering, S. V.; McMurry, P. H. (1991) Optical counter response to monodisperse atmospheric aerosols. *Atmos. Environ. Part A* 25: 463-468.
- Hering, S. V.; Lawson, D. R.; Allegrini, I.; Febo, A.; Perrino, C.; Possanzini, M.; Sickles, J. E., II; Anlauf, K. G.; Wiebe, A.; Appel, B. R.; John, W.; Ondo, J.; Wall, S.; Braman, R. S.; Sutton, R.; Cass, G. R.; Solomon, P. A.; Eatough, D. J.; Eatough, N. L.; Ellis, E. C.; Grosjean, D.; Hicks, B. B.; Womack, J. D.; Horrocks, J.; Knapp, K. T.; Ellestad, T. G.; Paur, R. J.; Mitchell, W. J.; Pleasant, M.; Peake, E.; MacLean, A.; Pierson, W. R.; Brachaczek, W.; Schiff, H. I.; Mackay, G. I.; Spicer, C. W.; Stedman, D. H.; Winer, A. M.; Biermann, H. W.; Tuazon, E. C. (1988) The nitric acid shootout: field comparison of measurement methods. *Atmos. Environ.* 22: 1519-1539.
- Hicks, B. B. (1984) Dry deposition processes. In: Altshuller, A. P.; Linthurst, R. A., eds. *Acidic deposition phenomenon and its effects: critical assessment review papers, volume I, atmospheric sciences*. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development; pp. 7-1 to 7-70; EPA report no. EPA/600/8-83/016AF. Available from: NTIS, Springfield, VA; PB85-100030.
- Hicks, B. B.; Meyers, T. P. (1989) Atmosphere-surface exchange processes. Presented at: 82nd annual meeting of the Air & Waste Management Association; June; Anaheim, CA. Pittsburgh, PA: Air & Waste Management Association; paper no. 89-113.4.

- Hicks, B. B.; Wesely, M. L.; Lindberg, S. E.; Bromberg, S. M., eds. (1986) Proceedings of the NAPAP workshop on dry deposition; March; Harpers Ferry, WV. Oak Ridge, TN: National Oceanic and Atmospheric Administration.
- Hicks, B. B.; Draxler, R. R.; Dodge, M.; Hales, J. M.; Albritton, D. L.; Schwartz, S. E.; Meyers, T. P.; Fehsenfeld, F. C.; Tanner, R. L.; Vong, R. J. (1991) Atmospheric processes research and process model development. In: Irving, P. M., ed. Acidic deposition: state of science and technology, volume I: emissions, atmospheric processes, and deposition. Washington, DC: The U.S. National Acid Precipitation Assessment Program. (State of science and technology report no. 2).
- Hildemann, L. M. (1990) A study of the origin of atmospheric organic aerosols [Ph.D. thesis]. Pasadena, CA: California Institute of Technology. Available from: University Microfilms, Ann Arbor, MI; order no. AAC90-14378.
- Hildemann, L. M.; Russell, A. G.; Cass, G. R. (1984) Ammonia and nitric acid concentrations in equilibrium with atmospheric aerosols: experiment vs theory, *Atmos. Environ.* 18: 1737-1750.
- Hildemann, L. M.; Cass, G. R.; Mazurek, M. A.; Simoneit, B. R. T. (1993) Mathematical modeling of urban organic aerosol: properties measured by high-resolution gas chromatography. *Environ. Sci. Technol.* 27: 2045-2055.
- Hildemann, L. M.; Klinedinst, D. B.; Klouda, G. A.; Currie, L. A.; Cass, G. R. (1994a) Sources of urban contemporary carbon aerosol. *Environ. Sci. Technol.* 28: 1565-1576.
- Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1994b) Seasonal trends in Los Angeles ambient organic aerosol observed by high-resolution gas chromatography. *Aerosol Sci. Technol.* 20: 303-317.
- Hill, T. A.; Choularton, T. W.; Penkett, S. A. (1986) A model of sulphate production in a cap cloud and subsequent turbulent deposition onto the hill surface. *Atmos. Environ.* 20: 1763-1771.
- Hinds, W. C. (1982) Aerosol technology. New York, NY: John Wiley and Sons.
- Hobbs, P. V.; Bowdle, D. A.; Radke, L. F. (1985) Particles in the lower troposphere over the high plains of the United States. Part I: size distributions, elemental compositions and morphologies. *J. Clim. Appl. Meteorol.* 24: 1344-1356.
- Hoffmann, M. R.; Boyce, S. D. (1983) Catalytic autooxidation of aqueous sulfur dioxide in relationship to atmospheric systems. *Adv. Environ. Sci. Technol.* 12: 147-189.
- Hoffmann, M. R.; Calvert, J. G. (1985) Chemical transformation modules for Eulerian acid deposition models: volume II, the aqueous-phase chemistry. Research Triangle Park, NC: U.S. Environmental Protection Agency, Atmospheric Sciences Research Laboratory; EPA report no. EPA/600/3-85/036. Available from: NTIS, Springfield, VA; PB85-198653/AS.
- Hoffmann, M. R.; Edwards, J. O. (1975) Kinetics of the oxidation of sulfite by hydrogen peroxide in acidic solution. *J. Phys. Chem.* 79: 2096-2098.
- Hoffmann, M. R.; Jacob, D. J. (1984) Kinetics and mechanisms of the catalytic oxidation of dissolved sulfur dioxide in aqueous solution: an application to nighttime fog water chemistry. In: Calvert, J. G., ed. *SO₂, NO and NO₂ oxidation mechanisms: atmospheric considerations*. Boston, MA: Butterworth Publishers; pp. 101-172. (Teasley, J. I., ed. *Acid precipitation series: v. 3*).
- Hoffmann, H. E.; Kuehnemann, W. (1979) Comparison of the results of two measuring methods determining the horizontal standard visibility with the visual visibility range. *Atmos. Environ.* 13: 1629-1634.

- Holsen, T. M.; Noll, K. E.; Fang, G.-C.; Lee, W.-J.; Lin, J.-M.; Keeler, G. J. (1993) Dry deposition and particle size distributions measured during the Lake Michigan Urban Air Toxics Study. *Environ. Sci. Technol.* 27: 1327-1333.
- Hong, M.-S.; Carmichael, G. R. (1986a) An investigation of sulfate production in an orographic storm using a detailed transport/chemistry model coupled with a detailed cloud scavenging model. *Atmos. Environ.* 20: 1989-1997.
- Hong, M.-S.; Carmichael, G. R. (1986b) Examination of a subgrid-scale parameterization for the transport of pollutants in a nonprecipitating cumulus cloud ensemble. *Atmos. Environ.* 20: 2205-2217.
- Hoppel, W. A. (1988) The role of non-precipitating cloud cycles and gas-to-particle conversion in the maintenance of the submicron aerosol size distribution over the tropical oceans. In: Hobbs, P. V.; McCormick, M. P., eds. *Aerosols and climate*. Hampton, VA: A. Deepak Publishers; pp. 9-19.
- Hoppel, W. A.; Frick, G. M. (1990) Submicron aerosol size distributions measured over the tropical and South Pacific. *Atmos. Environ. Part A* 24: 645-659.
- Hoppel, W. A.; Frick, G. M.; Larson, R. E. (1986) Effect of nonprecipitating clouds on the aerosol size distribution in the marine boundary layer. *Geophys. Res. Lett.* 13: 125-128.
- Hoppel, W. A.; Fitzgerald, J. W.; Frick, G. M.; Larson, R. E., et al. (1990) Aerosol size distributions and optical properties found in the marine boundary layer over the Atlantic Ocean. *J. Geophys. Res. [Atmos.]* 95: 3659-3686.
- Hoppel, W. A.; Frick, G. M.; Fitzgerald, J.; Larson, R. E. (1994) Marine boundary layer measurements of new particle formation and the effects nonprecipitating clouds have on aerosol size distribution. *J. Geophys. Res. [Atmos.]* 99: 14,443-14,459.
- Horvath, H.; Noll, K. E. (1969) The relationship between atmospheric light scattering coefficient and visibility. *Atmos. Environ.* 3: 543-550.
- Hosker, R. P., Jr.; Lindberg, S. E. (1982) Review: atmospheric deposition and plant assimilation of gases and particles. *Atmos. Environ.* 16: 889-910.
- Hov, O.; Isaksen, I. S. A. (1981) Generation of secondary pollutants in a power plant plume: a model study. *Atmos. Environ.* 15: 2367-2376.
- Huang, P.-F.; Turpin, B. J.; Pihlo, M. J.; Kittelson, D. B.; McMurry, P. H. (1994) Effects of water condensation and evaporation on diesel chain-agglomerate morphology. *J. Aerosol Sci.* 25: 447-459.
- Hubbe, J. M. (1989) Assessing procedures for estimating deposition rates for pollutants of interest. Sacramento, CA: California Air Resources Board, San Joaquin Valley Air Pollution Study Agency; San Joaquin Valley Air Quality Study technical support study no. 8.
- Hudischewskyj, A. B.; Seigneur, C. (1989) Mathematical modeling of the chemistry and physics of aerosols in plumes. *Environ. Sci. Technol.* 23: 413-421.
- Huntzicker, J. J.; Hoffman, R. S.; Ling, C.-S. (1978) Continuous measurement and speciation of sulfur-containing aerosols by flame photometry. *Atmos. Environ.* 12: 83-88.
- Huntzicker, J. J.; Cary, R. A.; Ling, C.-S. (1980) Neutralization of sulfuric acid aerosol by ammonia. *Environ. Sci. Technol.* 14: 819-824.
- Huntzicker, J. J.; Johnson, R. L.; Shah, J. J.; Cary, R. A. (1982) Analysis of organic and elemental carbon in ambient aerosols by a thermal-optical method. In: Wolff, G. T.; Klimisch, R. L., eds. *Particulate carbon - atmospheric*

- life cycle: proceedings of an international symposium; October 1980; Warren, MI. New York, NY: Plenum Press; pp. 79-88.
- Husain, L.; Dutkiewicz, V. A.; Hussain, M. M.; Khwaja, H. A.; Burkhard, E. G.; Mehmood, G.; Parekh, P. P.; Canelli, E. (1991) A study of heterogeneous oxidation of SO_2 in summer clouds. *J. Geophys. Res. [Atmos.]* 96: 18,789-18,805.
- Husar, R. B.; Gillani, N. V.; Husar, J. D. (1976) Particulate sulfur formation in power plant: urban and regional plumes. Presented at: Symposium on aerosol science and technology at the 82nd national meeting of the AIChE; August-September; Atlantic City, MD.
- Husar, R. B.; Patterson, D. E.; Husar, J. D.; Gillani, N. V.; Wilson, W. E., Jr. (1978) Sulfur budget of a power plant plume. In: Husar, R. B.; Lodge, J. P., Jr.; Moore, D. J., eds. *Sulfur in the atmosphere: proceedings of the international symposium*; September 1977; Dubrovnik, Yugoslavia. *Atmos. Environ.* 12: 549-568.
- Husar, R. B.; Holloway, J. M.; Patterson, D. E.; Wilson, W. E. (1981) Spatial and temporal pattern of eastern U.S. haziness: a summary. *Atmos. Environ.* 15: 1919-1928.
- Huss, A., Jr.; Lim, P. K.; Eckert, C. A. (1982a) Oxidation of aqueous sulfur dioxide. 1. Homogeneous manganese(II) and iron(II) catalysis at low pH. *J. Phys. Chem.* 86: 4224-4228.
- Huss, A., Jr.; Lim, P. K.; Eckert, C. A. (1982b) Oxidation of aqueous sulfur dioxide. 2. High-pressure studies and proposed reaction mechanisms. *J. Phys. Chem.* 86: 4229-4233.
- Ibusuki, T.; Takeuchi, K. (1987) Sulfur dioxide oxidation by oxygen catalyzed by mixtures of manganese(II) and iron(III) in aqueous solutions at environmental reaction conditions. *Atmos. Environ.* 21: 1555-1560.
- Irwin, J. S. (1983) Estimating plume dispersion—a comparison of several sigma schemes. *J. Clim. Appl. Meteorol.* 22: 92-114.
- Isaksen, I. S. A.; Hov, O.; Hesstvedt, E. (1978) Ozone generation over rural areas. *Environ. Sci. Technol.* 12: 1279-1284.
- Izumi, K.; Fukuyama, T. (1990) Photochemical aerosol formation from aromatic hydrocarbons in the presence of NO_x . *Atmos. Environ. Part A* 24: 1433-1441.
- Izumi, K.; Murano, K.; Mizuochi, M.; Fukuyama, T. (1988) Aerosol formation by the photooxidation of cyclohexene in the presence of nitrogen oxides. *Environ. Sci. Technol.* 22: 1207-1215.
- Jackson, M. L.; Gillette, D. A.; Danielsen, E. F.; Blifford, I. H.; Bryson, R. A.; Syers, J. K. (1973) Global dustfall during the quaternary as related to environments. *Soil Sci.* 116: 135-145.
- Jacob, D. J. (1986) Chemistry of OH in remote clouds and its role in the production of formic acid and peroxymonosulfate. *J. Geophys. Res. [Atmos.]* 91: 9807-9826.
- Jacob, D. J.; Hoffmann, M. R. (1983) A dynamic model for the production of H^+ , NO_3^- , and SO_4^{2-} in urban fog. *J. Geophys. Res. C: Oceans Atmos.* 88: 6611-6621.
- Jacob, D. J.; Waldman, J. M.; Munger, J. W.; Hoffmann, M. R. (1985) Chemical composition of fogwater collected along the California coast. *Environ. Sci. Technol.* 19: 730-736.
- Jacob, D. J.; Munger, J. W.; Waldman, J. M.; Hoffmann, M. R. (1986a) The H_2SO_4 - HNO_3 - NH_3 system at high humidities and in fogs: 1. spatial and temporal patterns in the San Joaquin Valley of California. *J. Geophys. Res. [Atmos.]* 91: 1073-1088.

- Jacob, D. J.; Waldman, J. M.; Munger, J. W.; Hoffmann, M. R. (1986b) The $\text{H}_2\text{SO}_4\text{-HNO}_3\text{-NH}_3$ system at high humidities and in fogs: 2. comparison of field data with thermodynamic calculations. *J. Geophys. Res. [Atmos.]* 91: 1089-1096.
- Jaffrezo, J.-L.; Colin, J.-L. (1988) Rain-aerosol coupling in urban area: scavenging ratio measurement and identification of some transfer processes. *Atmos. Environ.* 22: 929-935.
- Japar, S. M.; Brachaczek, W. W.; Gorse, R. A., Jr.; Norbeck, J. M.; Pierson, W. R. (1986) The contribution of elemental carbon to the optical properties of rural atmospheric aerosols. *Atmos. Environ.* 20: 1281-1289.
- Jassim, J. A.; Lu, H. P.; Chughtai, A. R.; Smith, D. M. (1986) The origin of infrared absorption bands of soot in the region 750 to 900 cm^{-1} . *Appl. Spectrosc.* 40: 113-116.
- John, W.; Sethi, V. (1993) Threshold for resuspension by particle impactation. *Aerosol Sci. Technol.* 19: 69-79.
- John, W.; Wang, H.-C. (1991) Laboratory testing method for PM-10 samplers: lowered effectiveness from particle loading. *Aerosol Sci. Technol.* 14: 93-101.
- John, W.; Wall, S. M.; Ondo, J. L.; Winklmayr, W. (1990) Modes in the size distributions of atmospheric inorganic aerosol. *Atmos. Environ. Part A* 24: 2349-2359.
- John, W.; Winklmayr, W.; Wang, H.-C. (1991) Particle deagglomeration and reentrainment in a PM-10 sampler. *Aerosol Sci. Technol.* 14: 165-176.
- Johnson, R. L.; Shah, J. J.; Cary, R. A.; Huntzicker, J. J. (1981) An automated thermal-optical method for the analysis of carbonaceous aerosol. In: Macias, E. S.; Hopke, P. K., eds. *Atmospheric aerosol: source/air quality relationships; based on a symposium jointly sponsored by the Divisions of Nuclear Chemistry and Technology at the 180th national meeting of the American Chemical Society; August 1980; Las Vegas, NV.* Washington, DC: American Chemical Society; pp. 223-233. (Comstock, M. J., ed. ACS symposium series: 167).
- Johnson, C. A.; Sigg, L.; Zobrist, J. (1987) Case studies on the chemical composition of fogwater: the influence of local gaseous emissions. *Atmos. Environ.* 21: 2365-2374.
- Joos, F.; Baltensperger, U. (1991) A field study on chemistry, S(IV) oxidation rates and vertical transport during fog conditions. *Atmos. Environ. Part A* 25: 217-230.
- Junge, C. E. (1963) *Air chemistry and radioactivity.* New York, NY: Academic Press. (Van Mieghem, J.; Hales, A. L., eds. *International geophysics series*: v. 4).
- Junge, C. E. (1977) Basic considerations about trace constituents in the atmosphere as related to the fate of global pollutants. In: Suffet, I. H., ed. *Fate of pollutants in the air and water environments: part I, mechanism of interaction between environments and mathematical modeling and the physical fate of pollutants, papers from the 165th national American Chemical Society meeting; April 1975; Philadelphia, PA.* New York, NY: John Wiley & Sons; pp. 7-25. (*Advances in environmental science and technology*: v. 8).
- Junge, C.; McLaren, E. (1971) Relationship of cloud nuclei spectra to aerosol size distribution and composition. *J. Atmos. Sci.* 28: 382-390.
- Kadowaki, S. (1994) Characterization of carbonaceous aerosols in the Nagoya urban area. 2. Behavior and origin of particulate *n*-alkanes. *Environ. Sci. Technol.* 28: 129-135.
- Kahl, J. D.; Samson, P. J. (1986) Uncertainty in trajectory calculations due to low resolution meteorological data. *J. Clim. Appl. Meteorol.* 25: 1816-1831.
- Kahl, J. D.; Samson, P. J. (1988) Trajectory sensitivity to rawinsonde data resolution. *Atmos. Environ.* 22: 1291-1299.

- Kahl, J. D.; Schnell, R. C.; Sheridan, P. J.; Zak, B. D.; Church, H. W.; Mason, A. S.; Heffter, J. L.; Harris, J. M. (1991) Predicting atmospheric debris transport in real-time using a trajectory forecast model. *Atmos. Environ. Part A* 25: 1705-1713.
- Kamens, R. M.; Jeffries, H. E.; Gery, M. W.; Wiener, R. W.; Sexton, K. G.; Howe, G. B. (1981) The impact of α -pinene on urban smog formation: an outdoor smog chamber study. *Atmos. Environ.* 15: 969-981.
- Kamens, R. M.; Gery, M. W.; Jeffries, H. E.; Jackson, M.; Cole, E. I. (1982) Ozone-isoprene reactions: product formation and aerosol potential. *Int. J. Chem. Kinet.* 14: 955-975.
- Kamens, R.; Odum, J.; Fan, Z.-H. (1995) Some observations on times to equilibrium for semivolatile polycyclic aromatic hydrocarbons. *Environ. Sci. Technol.* 29: 43-50.
- Kaplan, I. R.; Gordon, R. J. (1994) Non-fossil-fuel fine-particle organic carbon aerosols in Southern California determined during the Los Angeles Aerosol Characterization and Source Apportionment Study. *Aerosol Sci. Technol.* 21: 343-359.
- Karamchandani, P.; Venkatram, A. (1992) The role of non-precipitating clouds in producing ambient sulfate during summer: results from simulations with the Acid Deposition and Oxidant Model (ADOM) *Atmos. Environ. Part A* 26: 1041-1052.
- Katrinak, K. A.; Rez, P.; Buseck, P. R. (1992) Structural variations in individual carbonaceous particles from an urban aerosol. *Environ. Sci. Technol.* 26: 1967-1976.
- Katrinak, K. A.; Rez, P.; Perkes, P. R.; Buseck, P. R. (1993) Fractal geometry of carbonaceous aggregates from an urban aerosol. *Environ. Sci. Technol.* 27: 539-547.
- Kawamura, K.; Ng, L.-L.; Kaplan, I. R. (1985) Determination of organic acids (C_1 - C_{10}) in the atmosphere, motor exhausts, and engine oils. *Environ. Sci. Technol.* 19: 1082-1086.
- Keeler, G. J.; Brachaczek, W. W.; Gorse, R. A., Jr.; Japar, S. M.; Pierson, W. R. (1988) Effect of ambient humidity on dichotomous sampler coarse/fine ratios. *Atmos. Environ.* 22: 1715-1720.
- Keeler, G. J.; Japar, S. M.; Brachaczek, W. W.; Gorse, R. A., Jr.; Norbeck, J. M.; Pierson, W. R. (1990) The sources of aerosol elemental carbon at Allegheny Mountain. *Atmos. Environ. Part A* 24: 2795-2805.
- Kelly, N. A. (1987) The photochemical formation and fate of nitric acid in the metropolitan Detroit area: ambient, captive-air irradiation and modeling results. *Atmos. Environ.* 21: 2163-2177.
- Kelly, T. J.; Schwartz, S. E.; Daum, P. H. (1989) Detectability of acid producing reactions in natural clouds. *Atmos. Environ.* 23: 569-583.
- Kerminen, V. M.; Wexler, A. S. (1994a) Particle formation due to SO_2 oxidation and high relative humidity in the remote marine boundary layer. *J. Geophys. Res. [Atmos.]* 99: 25607-25625.
- Kerminen, V.-M.; Wexler, A. S. (1994b) Post-fog nucleation of H_2SO_4 - H_2O particles in smog. *Atmos. Environ.* 28: 2399-2406.
- Khlystov, A.; ten Brink, H. M.; Wyers, G. P. (1993) Hygroscopic growth rates of aerosols at high relative humidity. Petten, The Netherlands: Netherlands Energy Research Foundation ECN; report no. ECN-C-93-011.
- Kim, Y. J. (1995) Response of the Active Scattering Aerosol Spectrometer Probe (ASASP-100X) to particles of different chemical composition. *Aerosol Sci. Technol.* 22: 33-42.

- Kim, D.; Hopke, P. K. (1988) Classification of individual particles based on computer-controlled scanning electron microscopy data. *Aerosol Sci. Technol.* 9: 133-151.
- Kim, Y. P.; Seinfeld, J. H. (1995) Atmospheric gas-aerosol equilibrium: III. Thermodynamics of crustal elements Ca^{2+} , K^+ , and Mg^{2+} . *Aerosol Sci. Technol.* 22: 93-110.
- Kim, M. G.; Yagawa, K.; Inoue, H.; Lee, Y. K.; Shirai, T. (1990) Measurement of tire tread in urban air by pyrolysis-gas chromatography with flame photometric detection. *Atmos. Environ. Part A* 24: 1417-1422.
- Kim, Y. P.; Seinfeld, J. H.; Saxena, P. (1993a) Atmospheric gas-aerosol equilibrium: I. thermodynamic model. *Aerosol Sci. Technol.* 19: 157-181.
- Kim, Y. P.; Seinfeld, J. H.; Saxena, P. (1993b) Atmospheric gas-aerosol equilibrium: II. analysis of common approximations and activity coefficient calculation methods. *Aerosol Sci. Technol.* 19: 182-198.
- Kim, Y. J.; Boatman, J. F.; Gunter, R. L.; Wellman, D. L.; Wilkison, S. W. (1993c) Vertical distribution of atmospheric aerosol size distribution over south-central New Mexico. *Atmos. Environ. Part A* 27: 1351-1362.
- Kim, Y. P.; Pun, B. K.-L.; Chan, C. K.; Flagan, R. C.; Seinfeld, J. H. (1994) Determination of water activity in ammonium sulfate and sulfuric acid mixtures using levitated single particles. *Aerosol Sci. Technol.* 20: 275-284.
- Kitsa, V.; Liroy, P. J. (1992) Near field dispersion of mechanically resuspended dust from an unpaved road. *Transactions AWMA* 1: 199-210.
- Kitsa, V.; Liroy, P. J.; Chow, J. C.; Watson, J. G.; Shupack, S.; Howell, T.; Sanders, P. (1992) Particle-size distribution of chromium: total and hexavalent chromium in inspirable, thoracic, and respirable soil particles from contaminated sites in New Jersey. *Aerosol Sci. Technol.* 17: 213-229.
- Klee, A. J. (1984) Source control - municipal solid waste incinerators. In: Calvert, S.; Englund, H. M., eds. *Handbook of air pollution technology*. New York, NY: John Wiley & Sons; pp. 513-550.
- Klouda, G. A.; Currie, L. A.; Verkouteren, R. M.; Einfeld, W.; Zak, B. D. (1988) Advances in microradiocarbon dating and the direct tracing of environmental carbon. *J. Radioanal. Nucl. Chem.* 123: 191-197.
- Koenig, L. R.; Murray, F. W. (1976) Ice-bearing cumulus cloud evolution: numerical simulation and general comparison against observations. *J. Appl. Meteorol.* 15: 747-762.
- Köhler, H. (1936) The nucleus in and the growth of hygroscopic droplets. *Trans. Faraday Soc.* 32: 1152-1161.
- Kolb, C. E.; Jayne, J. T.; Worsnop, D. R.; Molina, M. J.; Meads, R. F.; Viggiano, A. A. (1994) Gas phase reaction of sulfur trioxide with water vapor. *J. Am. Chem. Soc.* 116: 10314-10315.
- Koutrakis, P.; Wolfson, J. M.; Slater, J. L.; Brauer, M.; Spengler, J. D.; Stevens, R. K.; Stone, C. L. (1988a) Evaluation of an annular denuder/filter pack system to collect acidic aerosols and gases. *Environ. Sci. Technol.* 22: 1463-1468.
- Koutrakis, P.; Wolfson, J. M.; Spengler, J. D. (1988b) An improved method for measuring aerosol strong acidity: results from a nine-month study in St. Louis, Missouri and Kingston, Tennessee. *Atmos. Environ.* 22: 157-162.
- Koutrakis, P.; Wolfson, J. M.; Spengler, J. D.; Stern, B.; Franklin, C. A. (1989) Equilibrium size of atmospheric aerosol sulfates as a function of the relative humidity. *J. Geophys. Res. [Atmos.]* 94: 6442-6448.

- Koutrakis, P.; Thompson, K. M.; Wolfson, J. M.; Spengler, J. D.; Keeler, G. J.; Slater, J. L. (1992) Determination of aerosol strong acidity losses due to interactions of collected particles: results from laboratory and field studies. *Atmos. Environ. Part A* 26: 987-995.
- Krieger, M. S.; Hites, R. A. (1992) Diffusion denuder for the collection of semivolatile organic compounds. *Environ. Sci. Technol.* 26: 1551-1555.
- Krieger, M. S.; Hites, R. A. (1994) Measurement of polychlorinated biphenyls and polycyclic aromatic hydrocarbons in air with a diffusion denuder. *Environ. Sci. Technol.* 28: 1129-1133.
- Kunen, S. M.; Lazrus, A. L.; Kok, G. L.; Heikes, B. G. (1983) Aqueous oxidation of SO₂ by hydrogen peroxide. *J. Geophys. Res. C: Oceans Atmos.* 88: 3671-3674.
- Kuo, Y.-H.; Skumanich, M.; Haagenson, P. L.; Chang, J. S. (1985) The accuracy of trajectory models as revealed by the observing system simulation experiments. *Mon. Weather Rev.* 113: 1852-1867.
- Lamb, B.; Guenther, A.; Gay, D.; Westberg, H. (1987) A national inventory of biogenic hydrocarbon emissions. *Atmos. Environ.* 21: 1695-1705.
- Lane, D. A.; Johnson, N. D.; Barton, S. C.; Thomas, G. H. S.; Schroeder, W. H. (1988) Development and evaluation of a novel gas and particle sampler for semivolatile chlorinated organic compounds in ambient air. *Environ. Sci. Technol.* 22: 941-947.
- Langner, J.; Rodhe, H. (1991) A global three-dimensional model of the tropospheric sulfur cycle. *J. Atmos. Chem.* 13: 225-263.
- Larson, S. M.; Cass, G. R. (1989) Characteristics of summer midday low-visibility events in the Los Angeles area. *Environ. Sci. Technol.* 23: 281-289.
- Larson, S. M.; Cass, G. R.; Gray, H. A. (1989) Atmospheric carbon particles and the Los Angeles visibility problem. *Aerosol Sci. Technol.* 10: 118-130.
- Lawrence, J. E.; Koutrakis, P. (1994) Measurement of atmospheric formic and acetic acids: methods evaluation and results from field studies. *Environ. Sci. Technol.* 28: 957-964.
- Lawson, D. R. (1990) The Southern California Air Quality Study. *J. Air Waste Manage. Assoc.* 40: 156-165.
- Lazrus, A. L.; Haagenson, P. L.; Kok, G. L.; Huebert, B. J.; Kreitzberg, C. W.; Likens, G. E.; Mohnen, V. A.; Wilson, W. E.; Winchester, J. W. (1983) Acidity in air and water in a case of warm frontal precipitation. *Atmos. Environ.* 17: 581-591.
- Leaitch, W. R.; Strapp, J. W.; Wiebe, H. A.; Isaac, G. A. (1983) Measurements of scavenging and transformation of aerosol inside cumulus. In: Pruppacher, H. R.; Semonin, R. G.; Slinn, W. G. N., eds. *Precipitation scavenging, dry deposition, and resuspension: proceedings of the fourth international conference, v. 1: precipitation scavenging*; November-December 1982; Santa Monica, CA. New York, NY: Elsevier; pp. 53-69.
- Leaitch, W. R.; Strapp, J. W.; Wiebe, H. A.; Anlauf, K. G.; Isaac, G. A. (1986a) Chemical and microphysical studies of nonprecipitating summer cloud in Ontario, Canada. *J. Geophys. Res. [Atmos.]* 91: 11,821-11,831.
- Leaitch, W. R.; Strapp, J. W.; Isaac, G. A.; Hudson, J. G. (1986b) Cloud droplet nucleation and cloud scavenging of aerosol sulphate in polluted atmospheres. *Tellus Ser. B* 38B: 328-344.
- Leaitch, W. R.; Bottenheim, J. W.; Strapp, J. W. (1988) Possible contribution of N₂O₅ scavenging to HNO₃ observed in winter stratiform cloud. *J. Geophys. Res. [Atmos.]* 93: 12,569-12,584.

- Lee, Y.-N.; Schwartz, S. E. (1983) Kinetics of oxidation of aqueous sulfur(IV) by nitrogen dioxide. In: Pruppacher, H. R.; Semonin, R. G.; Slinn, W. G. N., eds. Precipitation scavenging, dry deposition, and resuspension: proceedings of the fourth international conference, v. 1: precipitation scavenging; November-December 1982; Santa Monica, CA. New York, NY: Elsevier; pp. 453-470.
- Leone, J. A.; Flagan, R. C.; Grosjean, D.; Seinfeld, J. H. (1985) An outdoor smog chamber and modeling study of toluene-NO_x photooxidation. *Int. J. Chem. Kinet.* 17: 177-216.
- Lewis, R. S.; Deen, W. M. (1994) Kinetics of the reaction of nitric oxide with oxygen in aqueous solutions. *Chem. Res. Toxicol.* 7: 568-574.
- Lewis, C. W.; Baumgardner, R. E.; Stevens, R. K.; Claxton, L. D.; Lewtas, J. (1988) Contribution of woodsmoke and motor vehicle emissions to ambient aerosol mutagenicity. *Environ. Sci. Technol.* 22: 968-971.
- Li, W.; Montassier, N.; Hopke, P. K. (1992) A system to measure the hygroscopicity of aerosol particles. *Aerosol Sci. Technol.* 17: 25-35.
- Li, S.-M.; Anlauf, K. G.; Wiebe, H. A. (1993) Heterogeneous nighttime production and deposition of particle nitrate at a rural site in North America during summer 1988. *J. Geophys. Res. [Atmos.]* 98: 5139-5157.
- Liang, C. S. K.; Waldman, J. M. (1992) Indoor exposures to acidic aerosols at child and elderly care facilities. *Indoor Air* 2: 196-207.
- Liebsch, E. J.; de Pena, R. G. (1982) Sulfate aerosol production in coal-fired power plant plumes. *Atmos. Environ.* 16: 1323-1331.
- Ligocki, M. P.; Pankow, J. F. (1989) Measurements of the gas/particle distributions of atmospheric organic compounds. *Environ. Sci. Technol.* 23: 75-83.
- Ligocki, M. P.; Salmon, L. G.; Fall, T.; Jones, M. C.; Nazaroff, W. W.; Cass, G. R. (1993) Characteristics of airborne particles inside southern California museums. *Atmos. Environ. Part A* 27: 697-711.
- Lin, X.; Chameides, W. L. (1991) Model studies of the impact of chemical inhomogeneity on SO₂ oxidation in warm stratiform clouds. *J. Atmos. Chem.* 13: 109-129.
- Lin, J.-M.; Fang, G.-C.; Holsen, T. M.; Noll, K. E. (1993) A comparison of dry deposition modeled from size distribution data and measured with a smooth surface for total particle mass, lead and calcium in Chicago. *Atmos. Environ. Part A* 27: 1131-1138.
- Lin, J. J.; Noll, K. E.; Holsen, T. M. (1994) Dry deposition velocities as a function of particle size in the ambient atmosphere. *Aerosol Sci. Technol.* 20: 239-252.
- Lind, J. A.; Lazrus, A. L. (1983) Aqueous phase oxidation of sulfur IV by some organic peroxides [abstract]. *EOS Trans.* 64: 670.
- Lindberg, S. E. (1982) Factors influencing trace metal, sulfate and hydrogen ion concentrations in rain. *Atmos. Environ.* 16: 1701-1709.
- Linton, R. W.; Loh, A.; Natusch, D. F. S.; Evans, C. A., Jr.; Williams, P. (1976) Surface predominance of trace elements in airborne particles. *Science (Washington, DC)* 191: 852-854.
- Lioy, P. J.; Daisey, J. M. (1986) Airborne toxic elements and organic substances. *Environ. Sci. Technol.* 20: 8-14.
- Lioy, P. J.; Watson, J. G., Jr.; Spengler, J. D. (1980) APCA specialty conference workshop on baseline data for inhalable particulate matter. *J. Air Pollut. Control Assoc.* 30: 1126-1130.

- Lippmann, M. (1980) Size distributions in urban aerosols. In: Kneip, T. J.; Liou, P. J., eds. *Aerosols: anthropogenic and natural, sources and transport*. Ann. N. Y. Acad. Sci. 338: 1-12.
- Liu, P. S. K.; Leaitch, W. R.; Strapp, J. W.; Wasey, M. A. (1992) Response of particle measuring systems airborne to ASASP and PCASP to NaCl and latex particles. *Aerosol Sci. Technol.* 16: 83-95.
- Liu, P. S. K.; Leaitch, W. R.; Macdonald, A. M.; Isaac, G. A.; Strapp, J. W.; Wiebe, H. A. (1993) Sulphate production in summer cloud over Ontario, Canada. *Tellus Ser. B* 45B: 368-389.
- Lowenthal, D. H.; Rogers, C. F.; Saxena, P.; Watson, J. G.; Chow, J. C. (1995) Sensitivity of estimated light extinction coefficients to model assumptions and measurement errors. *Atmos. Environ.* 29: 751-766.
- Lundgren, D. A.; Burton, R. M. (1995) Effect of particle size distribution on the cut point between fine and coarse ambient mass fractions. In: Phalen, R. F.; Bates, D. V., eds. *Proceedings of the colloquium on particulate air pollution and human mortality and morbidity*; January 1994; Irvine, CA. *Inhalation Toxicol.* 7: 131-148.
- Lundgren, D. A.; Hausknecht, B. J. (1982a) Ambient aerosol mass distribution of 1 to 100 μm particles in five cities. Presented at: 75th annual meeting of the Air Pollution Control Association; June; New Orleans, LA. Pittsburgh, PA: Air Pollution Control Association; paper no. 82-45.4.
- Lundgren, D. A.; Hausknecht, B. J. (1982b) Ambient aerosol size distribution determination using a mobile wide range aerosol classifier. Research Triangle Park, NC: U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory; EPA contract no. CR-808606-01-1.
- Lundgren, D. A.; Hausknecht, B. J.; Burton, R. M. (1984) Large particle size distribution in five U.S. cities and the effect on a new ambient particulate matter standard (PM_{10}). *Aerosol Sci. Technol.* 7: 467-473.
- Lusis, M. A.; Anlauf, K. G.; Barrie, L. A.; Wiebe, H. A. (1978) Plume chemistry studies at a northern Alberta power plant. *Atmos. Environ.* 12: 2429-2437.
- Maahs, H. G. (1983) Kinetics and mechanism of the oxidation of S(IV) by ozone in aqueous solution with particular reference to SO_2 conversion in nonurban tropospheric clouds. *J. Geophys. Res. C: Oceans Atmos.* 88: 10,721-10,732.
- Macias, E. S.; Zwicker, J. O.; White, W. H. (1981) Regional haze case studies in the southwestern U.S.—II. source contributions. In: White, W. H.; Moore, D. J.; Lodge, J. P., Jr., eds. *Plumes and visibility: measurements and model components: proceedings of the symposium*; November 1980; Grand Canyon National Park, AZ. *Atmos. Environ.* 15: 1987-1997.
- Makhonko, K. P. (1986) Wind dust lift from the grass surface. *Meteorol. Gidrol.* 10: 61-65.
- Malm, W. C.; Gebhart, K. A.; Molenaar, J.; Cahill, T.; Eldred, R.; Huffman, D. (1994) Examining the relationship between atmospheric aerosols and light extinction at Mount Rainier and North Cascades National Parks. *Atmos. Environ.* 28: 347-360.
- Mamane, Y.; Stevens, R. K.; Dzubay, T. G. (1990) On the sources of fine and coarse carbon particles in the Great Lakes. *J. Aerosol Sci.* 21(suppl. 1): S353-S356.
- Mansoori, B. A.; Johnston, M. V.; Wexler, A. S. (1994) Quantitation of ionic species in single microdroplets by on-line laser desorption/ionization. *Anal. Chem.* 66: 3681-3687.
- Martin, L. R. (1984) Kinetic studies of sulfite oxidation in aqueous solution. In: Calvert, J. G., ed. SO_2 , NO and NO_2 oxidation mechanisms: atmospheric considerations. Boston, MA: Butterworth Publishers; pp. 63-100. (Teasley, J. I., ed. *Acid precipitation series*: v. 3).

- Martin, L. R. (1994) Aqueous sulfur(IV) oxidation revisited. In: Nriagu, J. O.; Simmons, M. S., eds. *Environmental oxidants*. New York, NY: John Wiley & Sons, Inc.; pp. 221-268. (Nriagu, J. O., ed. *Advances in environmental science and technology*: v. 28).
- Martin, L. R.; Damschen, D. E. (1981) Aqueous oxidation of sulfur dioxide by hydrogen peroxide at low pH. *Atmos. Environ.* 15: 1615-1621.
- Martin, L. R.; Hill, M. W. (1987a) The iron catalyzed oxidation of sulfur: reconciliation of the literature rates. *Atmos. Environ.* 21: 1487-1490.
- Martin, L. R.; Hill, M. W. (1987b) The effect of ionic strength on the manganese catalyzed oxidation of sulfur(IV). *Atmos. Environ.* 21: 2267-2270.
- Martin, L. R.; Hill, M. W.; Tai, A. F.; Good, T. W. (1991) The iron catalyzed oxidation of sulfur(IV) in aqueous solution: differing effects of organics at high and low pH. *J. Geophys. Res. [Atmos.]* 96: 3085-3097.
- Martonen, T. B. (1993) Mathematical model for the selective deposition of inhaled pharmaceuticals. *J. Pharm. Sci.* 82: 1191-1199.
- Mason, A. S.; Gifford, F. A. (1992) Atmospheric tracer dispersion over a 24-h time span. *Atmos. Environ. Part A* 26: 3203-3205.
- Mazurek, M. A.; Simoneit, B. R. T. (1984) Characterization of biogenic and petroleum-derived organic matter in aerosols over remote, rural and urban areas. In: Keith, L. H., ed. *Identification and analysis of organic pollutants in air: [papers from a symposium at the 184th national American Chemical Society meeting]; September 1982; Kansas City, MO*. Woburn, MA: Butterworth Publishers; pp. 353-370.
- Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1989) Interpretation of high-resolution gas chromatography / mass spectrometry data acquired from atmospheric organic aerosol samples. *Aerosol Sci. Technol.* 10: 408-420.
- Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1991) Biological input to visibility-reducing aerosol particles in the remote arid southwestern United States. *Environ. Sci. Technol.* 25: 684-694.
- McArdle, J. V.; Hoffmann, M. R. (1983) Kinetics and mechanism of the oxidation of aquated sulfur dioxide by hydrogen peroxide at low pH. *J. Phys. Chem.* 87: 5425-5429.
- McHenry, J. N.; Dennis, R. L. (1991) Partitioning of the sulfate budget into gas- and aqueous-phase components in the regional acid deposition model (RADM). In: *Proceedings of the 7th joint AMS-AWMA conference: applications of air pollution meteorology*; New Orleans, LA; pp. 143-147.
- McHenry, J. N.; Dennis, R. L. (1994) The relative importance of oxidation pathways and clouds to atmospheric ambient sulfate production as predicted by the Regional Acid Deposition Model. *J. Appl. Meteorol.* 33: 890-905.
- McMahon, T. A.; Denison, P. J. (1979) Empirical atmospheric deposition parameters—a survey. *Atmos. Environ.* 13: 571-585.
- McMurry, P. H.; Friedlander, S. K. (1979) New particle formation in the presence of an aerosol. *Atmos. Environ.* 13: 1635-1651.
- McMurry, P. H.; Grosjean, D. (1985) Photochemical formation of organic aerosols: growth laws and mechanisms. *Atmos. Environ.* 19: 1445-1451.
- McMurry, P. H.; Stolzenburg, M. R. (1989) On the sensitivity of particle size to relative humidity for Los Angeles aerosols. *Atmos. Environ.* 23: 497-507.

- McMurry, P. H.; Wilson, J. C. (1982) Growth laws for the formation of secondary ambient aerosols: implications for chemical conversion mechanisms. *Atmos. Environ.* 16: 121-134.
- McMurry, P. H.; Wilson, J. C. (1983) Droplet phase (heterogeneous) and gas phase (homogeneous) contributions to secondary ambient aerosol formation as functions of relative humidity. *J. Geophys. Res.* 88: 5101-5108.
- McMurry, P. H.; Zhang, X. Q. (1989) Size distributions of ambient organic and elemental carbon. *Aerosol Sci. Technol.* 10: 430-437.
- McMurry, P. H.; Rader, D. J.; Stith, J. L. (1981) Studies of aerosol formation in power plant plumes—I. growth laws for secondary aerosols in power plant plumes: implications for chemical conversion mechanisms. In: White, W. H.; Moore, D. J.; Lodge, J. P., Jr., eds. *Plumes and visibility: measurements and model components: proceedings of the symposium; November 1980; Grand Canyon National Park, AZ.* *Atmos. Environ.* 15: 2315-2327.
- McMurry, P. H.; Zhang, X.; Lee, C.-T. (1996) Issues in aerosol measurement. *J. Geophys. Res. [Atmos.]*: in press.
- McNider, R. T.; Moran, M. D.; Pielke, R. A. (1988) Influence of diurnal and inertial boundary-layer oscillations on long-range dispersion. *Atmos. Environ.* 22: 2445-2462.
- Meagher, J. F.; Stockburger, L.; Bailey, E. M.; Huff, O. (1978) The oxidation of sulfur dioxide to sulfate aerosols in the plume of a coal-fired power plant. *Atmos. Environ.* 12: 2197-2203.
- Meagher, J. F.; Stockburger, L., III; Bonanno, R. J.; Bailey, E. M.; Luria, M. (1981) Atmospheric oxidation of flue gases from coal-fired power plants—a comparison between conventional and scrubbed plumes. *Atmos. Environ.* 15: 749-762.
- Meagher, J. F.; Olszyna, K. J.; Weatherford, F. P.; Mohnen, V. A. (1990) The availability of H_2O_2 and O_3 for aqueous phase oxidation of SO_2 . The question of linearity. *Atmos. Environ. Part A* 24: 1825-1829.
- Meng, Z.; Seinfeld, J. H. (1994) On the source of the submicrometer droplet mode of urban and regional aerosols. *Aerosol Sci. Technol.* 20: 253-265.
- Meng, Z.; Seinfeld, J. H.; Saxena, P.; Kim, Y. P. (1995) Contribution of water to particulate mass in the South Coast Air Basin. *Aerosol Sci. Technol.* 22: 111-123.
- Michaud, D.; Baril, M.; Perrault, G. (1993) Characterization of airborne dust from cast iron foundries by physico-chemical methods and multivariate statistical analyses. *Air Waste* 43: 729-735.
- Milford, J. B.; Davidson, C. I. (1985) The sizes of particulate trace elements in the atmosphere—a review. *J. Air Pollut. Control Assoc.* 35: 1249-1260.
- Milford, J. B.; Davidson, C. I. (1987) The sizes of particulate sulfate and nitrate in the atmosphere—a review. *JAPCA* 37: 125-134.
- Miller, D. F.; Alkezweeny, A. J. (1980) Aerosol formation in urban plumes over Lake Michigan. In: Kneip, T. J.; Liou, P. J., eds. *Aerosols: anthropogenic and natural, sources and transport.* *Ann. N. Y. Acad. Sci.* 338: 219-232.
- Miller, F. J.; Gardner, D. E.; Graham, J. A.; Lee, R. E., Jr.; Wilson, W. E.; Bachmann, J. D. (1979) Size considerations for establishing a standard for inhalable particles. *J. Air Pollut. Control Assoc.* 29: 610-615.
- Mohnen, V. A.; Kadlec, J. A. (1989) Cloud chemistry research at Whiteface Mountain. *Tellus Ser. B* 41B: 79-91.
- Moran, M. D. (1992) Numerical modeling of mesoscale atmospheric dispersion [Ph.D. dissertation]. Ft. Collins, CO: Colorado State University, Department of Atmospheric Science.

- Morandi, M. T. (1985) Development of source apportionment models for inhalable particulate matter and its extractable organic fractions in urban areas of New Jersey [Ph.D. dissertation]. Syracuse, NY: New York University. Available from: University Microfilms, Ann Arbor, MI; order no. AAC85-10516.
- Morandi, M. T.; Lioy, P. J.; Daisey, J. M. (1991) Comparison of two multivariate modeling approaches for the source apportionment of inhalable particulate matter in Newark, NJ. *Atmos. Environ. Part A* 25: 927-937.
- Moyers, J. L.; Ranweiler, L. E.; Hopf, S. B.; Korte, N. E. (1977) Evaluation of particulate trace species in southwest desert atmosphere. *Environ. Sci. Technol.* 11: 789-795.
- Mozurkewich, M.; Calvert, J. G. (1988) Reaction probability of N_2O_5 on aqueous aerosols. *J. Geophys. Res. [Atmos.]* 93: 15,889-15,896.
- Mueller, P. K.; Fung, K. K.; Heisler, S. L.; Grosjean, D.; Hidy, G. M. (1982) Atmospheric particulate carbon observations in urban and rural areas of the United States. In: Wolff, G. T.; Klimisch, R. L., eds. *Particulate carbon: atmospheric life cycle: proceedings of an international symposium; October 1980; Warren, MI.* New York, NY: Plenum Press; pp. 343-370.
- Mulhbaier, J. L.; Williams, R. L. (1982) Fireplaces, furnaces and vehicles as emission sources of particulate carbon. In: Wolff, G. T.; Klimisch, R. L., eds. *Particulate carbon: atmospheric life cycle.* New York, NY: Plenum Press; pp. 185-205.
- Munger, J. W.; Jacob, D. J.; Waldman, J. M.; Hoffmann, M. R. (1983) Fogwater chemistry in an urban atmosphere. *J. Geophys. Res. C: Oceans Atmos.* 88: 5109-5121.
- Munger, J. W.; Jacob, D. J.; Hoffmann, M. R. (1984) The occurrence of bisulfite-aldehyde addition products in fog- and cloudwater. *J. Atmos. Chem.* 1: 335-350.
- Munger, J. W.; Collett, J., Jr.; Daube, B., Jr.; Hoffmann, M. R. (1990) Fogwater chemistry at Riverside, California. *Atmos. Environ. Part B* 24: 185-205.
- Mylonas, D. T.; Allen, D. T.; Ehrman, S. H.; Pratsinis, S. E. (1991) The sources and size distributions of organonitrates in Los Angeles aerosol. *Atmos. Environ. Part A* 25: 2855-2861.
- Nair, S. K.; Peters, L. K. (1989) Studies on non-precipitating cumulus cloud acidification. *Atmos. Environ.* 23: 1399-1423.
- National Research Council. (1979) *Airborne particles.* Baltimore, MD: University Park Press.
- National Research Council. (1983) *Polycyclic aromatic hydrocarbons: evaluation of sources and effects.* Washington, DC: National Academy Press.
- National Research Council. (1993) *Protecting visibility in national parks and wilderness areas.* Washington, DC: National Academy Press. 3v.
- Newman, L. (1981) Atmospheric oxidation of sulfur dioxide: a review as viewed from power plant and smelter plume studies. *Atmos. Environ.* 15: 2231-2239.
- Newman, L.; Forrest, J.; Manowitz, B. (1975a) The application of an isotopic ratio technique to a study of the atmospheric oxidation of sulfur dioxide in the plume from an oil-fired power plant. *Atmos. Environ.* 9: 959-968.
- Newman, L.; Forrest, J.; Manowitz, B. (1975b) The application of an isotopic ratio technique to a study of the atmospheric oxidation of sulfur dioxide in the plume from a coal fired power plant. *Atmos. Environ.* 9: 969-977.

- Nicholson, K. W. (1988) The dry deposition of small particles: a review of experimental measurements. *Atmos. Environ.* 22: 2653-2666.
- Nielsen, T. (1984) Reactivity of polycyclic aromatic hydrocarbons toward nitrating species. *Environ. Sci. Technol.* 18: 157-163.
- Nielsen, T.; Ramdahl, T.; Bjørseth, A. (1983) The fate of airborne polycyclic organic matter. *Environ. Health Perspect.* 47: 103-114.
- Noone, K. J.; Ogren, J. A.; Hallberg, A.; Hansson, H.-C.; Wiedensohler, A.; Swietlicki, E. (1992a) A statistical examination of the chemical differences between interstitial and scavenged aerosol. *Tellus Ser. B* 44B: 581-592.
- Noone, K. J.; Ogren, J. A.; Hallberg, A.; Heintzenberg, J.; Ström, J.; Hansson, H.-C.; Svenningsson, B.; Wiedensohler, A.; Fuzzi, S.; Facchini, M. C.; Arends, B. G.; Berner, A. (1992b) Changes in aerosol size- and phase distributions due to physical and chemical processes in fog. *Tellus Ser. B* 44B: 489-504.
- Novakov, T. (1984) The role of soot and primary oxidants in the atmospheric chemistry. *Sci. Total Environ.* 36: 1-10.
- Novakov, T.; Penner, J. E. (1993) Large contribution of organic aerosols to cloud-condensation-nuclei concentrations. *Nature (London)* 365: 823-826.
- Noxon, J. F. (1983) NO_3 and NO_2 in the mid-Pacific troposphere. *J. Geophys. Res. C: Oceans Atmos.* 88: 11,017-11,021.
- Nunes, T. V.; Pio, C. A. (1993) Carbonaceous aerosols in industrial and coastal atmospheres. *Atmos. Environ. Part A* 27: 1339-1346.
- Oberdörster, G. (1995) Lung particle overload: implications for occupational exposures to particles. *Regul. Toxicol. Pharmacol.* 27: 123-135.
- O'Brien, R. J.; Crabtree, J. H.; Holmes, J. R.; Hoggan, M. C.; Bockian, A. H. (1975) Formation of photochemical aerosol from hydrocarbons: atmospheric analysis. *Environ. Sci. Technol.* 9: 577-582.
- O'Dell, R. A.; Taheri, M.; Kabel, R. L. (1977) A model for uptake of pollutants by vegetation. *J. Air Pollut. Control Assoc.* 27: 1104-1109.
- Ogren, J. A.; Charlson, R. J. (1992) Implications for models and measurements of chemical inhomogeneities among cloud droplets. *Tellus Ser. B* 44B: 208-225.
- Olmez, I.; Sheffield, A. E.; Gordon, G. E.; Houck, J. E.; Pritchett, L. C.; Cooper, J. A.; Dzubay, T. G.; Bennett, R. L. (1988) Compositions of particles from selected sources in Philadelphia for receptor modeling applications. *JAPCA* 38: 1392-1402.
- Olson, T. M.; Hoffman, M. R. (1989) Hydroxyalkylsulfonate formation: its role as a S(IV) reservoir in atmospheric water droplets. *Atmos. Environ.* 23: 985-997.
- Otani, Y.; Wang, C. S. (1984) Growth and deposition of saline droplets covered with a monolayer of surfactant. *Aerosol Sci. Technol.* 3: 155-166.
- Pack, D. H.; Ferber, G. J.; Heffter, J. L.; Telegadas, K.; Angell, J. K.; Hoecker, W. H.; Machta, L. (1978) Meteorology of long-range transport. *Atmos. Environ.* 12: 425-444.

- Palen, E. J.; Allen, D. T.; Pandis, S. N.; Paulson, S. E.; Seinfeld, J. H.; Flagan, R. C. (1992) Fourier transform infrared analysis of aerosol formed in the photo-oxidation of isoprene and β -pinene. *Atmos. Environ. Part A* 26: 1239-1251.
- Pandis, S. N.; Seinfeld, J. H. (1989a) Sensitivity analysis of a chemical mechanism for aqueous-phase atmospheric chemistry. *J. Geophys. Res. [Atmos.]* 94: 1105-1126.
- Pandis, S. N.; Seinfeld, J. H. (1989b) Mathematical modeling of acid deposition due to radiation fog. *J. Geophys. Res. [Atmos.]* 94: 12,911-12,923.
- Pandis, S. N.; Seinfeld, J. H.; Pilinis, C. (1990a) The smog-fog-smog cycle and acid deposition. *J. Geophys. Res. [Atmos.]* 95: 18,489-18,500.
- Pandis, S. N.; Seinfeld, J. H.; Pilinis, C. (1990b) Chemical composition differences in fog and cloud droplets of different sizes. *Atmos. Environ. Part A* 24: 1957-1969.
- Pandis, S. N.; Paulson, S. E.; Seinfeld, J. H.; Flagan, R. C. (1991) Aerosol formation in the photooxidation of isoprene and β -pinene. *Atmos. Environ. Part A* 25: 997-1008.
- Pandis, S. N.; Harley, R. A.; Cass, G. R.; Seinfeld, J. H. (1992a) Secondary organic aerosol formation and transport. *Atmos. Environ. Part A* 26: 2269-2282.
- Pandis, S. N.; Seinfeld, J. H.; Pilinis, C. (1992b) Heterogeneous sulfate production in an urban fog. *Atmos. Environ. Part A* 26: 2509-2522.
- Pandis, S. N.; Wexler, A. S.; Seinfeld, J. H. (1993) Secondary organic aerosol formation and transport—II. predicting the ambient secondary organic aerosol size distribution. *Atmos. Environ. Part A* 27: 2403-2416.
- Pankow, J. F. (1987) Review and comparative analysis of the theories on partitioning between the gas and aerosol particulate phases in the atmosphere. *Atmos. Environ.* 21: 2275-2283.
- Pankow, J. F. (1988) Gas phase retention volume behavior of organic compounds on the sorbent poly(oxy-*m*-terphenyl-2'-5'-ylene). *Anal. Chem.* 60: 950-958.
- Pankow, J. F. (1989) Overview of the gas phase retention volume behavior of organic compounds on polyurethane foam. *Atmos. Environ.* 23: 1107-1111.
- Pankow, J. F. (1991) Common y-intercept and single compound regressions of gas-particle partitioning data vs. $1/T$. *Atmos. Environ. Part A* 25: 2229-2239.
- Pankow, J. F. (1994a) An absorption model of gas/particle partitioning of organic compounds in the atmosphere. *Atmos. Environ.* 28: 185-188.
- Pankow, J. F. (1994b) An absorption model of the gas/aerosol partitioning involved in the formation of secondary organic aerosol. *Atmos. Environ.* 28: 189-193.
- Pankow, J. F.; Bidleman, T. F. (1991) Effects of temperature, *TSP* and per cent non-exchangeable material in determining the gas-particle partitioning of organic compounds. *Atmos. Environ. Part A* 25: 2241-2249.
- Pankow, J. F.; Bidleman, T. F. (1992) Interdependence of the slopes and intercepts from log-log correlations of measured gas-particle partitioning and vapor pressure - I. theory and analysis of available data. *Atmos Environ. Part A* 26: 1071-1080.
- Pankow, J. F.; Storey, J. M. E.; Yamasaki, H. (1993) Effects of relative humidity on gas/particle partitioning of semivolatile organic compounds to urban particulate matter. *Environ. Sci. Technol.* 27: 2220-2226.

- Parrish, D. D.; Fahey, D. W.; Williams, E. J.; Liu, S. C.; Trainer, M.; Murphy, P. C.; Albritton, D. L.; Fehsenfeld, F. C. (1986) Background ozone and anthropogenic ozone enhancement at Niwot Ridge, Colorado. *J. Atmos. Chem.* 4: 63-80.
- Pasquill, F. (1974) *Atmospheric diffusion*. New York, NY: John Wiley and Sons.
- Pasquill, F.; Smith, F. B. (1983) *Atmospheric diffusion*. 3rd ed. New York, NY: John Wiley.
- Pastuszka, J. S.; Kwapulinski, J. (1988) The change in mass size distribution of aerosol near dumps as a result of resuspension of dust. Presented at: 81st annual meeting of Air Pollution Control Association; June; Dallas, TX. Pittsburgh, PA: Air Pollution Control Association; paper no. 88-151.3.
- Patrinos, A. A. N. (1985) The impact of urban and industrial emissions on mesoscale precipitation quality. *J. Air Pollut. Control Assoc.* 35: 719-727.
- Patrinos, A. A. N.; Brown, R. M. (1984) Mesoscale wetfall chemistry around Philadelphia during frontal storms. *Geophys. Res. Lett.* 11: 561-564.
- Patrinos, A. A. N.; Leach, M. J.; Brown, R. M.; Tanner, R. L.; Binkowski, F. S. (1989) An acid rain study in the Washington, D.C. area. *J. Appl. Meteorol.* 28: 948-968.
- Patterson, E. M.; Gillette, D. A. (1977a) Commonalities in measured size distributions for aerosols having a soil-derived component. *J. Geophys. Res.* 82: 2074-2082.
- Patterson, E. M.; Gillette, D. A. (1977b) Measurements of visibility vs. mass-concentration for airborne soil particles. *Atmos. Environ.* 11: 193-196.
- Patterson, R. K.; Wagman, J. (1977) Mass and composition of an urban aerosol as a function of particle size for several visibility levels. *J. Aerosol Sci.* 8: 269-279.
- Peirson, D. H.; Cawse, P. A.; Salmon, L.; Cambray, R. S. (1973) Trace elements in the atmospheric environment. *Nature (London)* 241: 252-256.
- Penkett, S. A. (1972) Oxidation of SO₂ and other atmospheric gases by ozone in aqueous solution. *Nature (London)* 240: 105-106.
- Penkett, S. A.; Jones, B. M. R.; Brice, K. A.; Eggleton, A. E. J. (1979) The importance of atmospheric ozone and hydrogen peroxide in oxidising sulphur dioxide in cloud and rainwater. *Atmos. Environ.* 13: 123-137.
- Penner, J. E.; Eddleman, H.; Novakov, T. (1993) Towards the development of a global inventory for black carbon emissions. *Atmos. Environ. Part A* 27: 1277-1295.
- Peters, K.; Eiden, R. (1992) Modelling the dry deposition velocity of aerosol particles to a spruce forest. *Atmos. Environ. Part A* 26: 2555-2564.
- Peterson, J. T.; Junge, C. E. (1971) Sources of particulate matter in the atmosphere. In: Matthews, W. H.; Kellogg, W. W.; Robinson, G. D., eds. *Man's impact on the climate*. Cambridge, MA: MIT Press.
- Pickle, T.; Allen, D. T.; Pratsinis, S. E. (1990) The sources and size distributions of aliphatic and carbonyl carbon in Los Angeles aerosol. *Atmos. Environ. Part A* 24: 2221-2228.
- Pielke, R. A.; et al. (1992) A comprehensive mesoscale modeling system - RAMS. *Meteorol. Atmos. Phys.* 49: 69-91.
- Pierson, W. R.; Brachaczek, W. W. (1983) Particulate matter associated with vehicles on the road. II. *Aerosol Sci. Technol.* 2: 1-40.

- Pierson, W. R.; Brachaczek, W. W. (1990) Dew chemistry and acid deposition in Glendora, California, during the 1986 Carbonaceous Species Methods Comparison Study. *Aerosol Sci. Technol.* 12: 8-27.
- Pierson, W. R.; Brachaczek, W. W.; Gorse, R. A., Jr.; Japar, S. M.; Norbeck, J. M. (1986) On the acidity of dew. *J. Geophys. Res. [Atmos.]* 91: 4083-4096.
- Pierson, W. R.; Brachaczek, W. W.; Japar, S. M.; Cass, G. R.; Solomon, P. A. (1988) Dry deposition and dew chemistry in Claremont, California, during the 1985 Nitrogen Species Methods Comparison Study. *Atmos. Environ.* 22: 1657-1663.
- Pilinis, C.; Seinfeld, J. H. (1987) Continued development of a general equilibrium model for inorganic multicomponent atmospheric aerosols. *Atmos. Environ.* 21: 2453-2466.
- Pilinis, C.; Seinfeld, J. H. (1988) Development and evaluation of an Eulerian photochemical gas-aerosol model. *Atmos. Environ.* 22: 1985-2001.
- Pilinis, C.; Seinfeld, J. H.; Grosjean, D. (1989) Water content of atmospheric aerosols. *Atmos. Environ.* 23: 1601-1606.
- Pinnick, R. G.; Fernandez, G.; Hinds, B. D.; Bruce, C. W.; Schaefer, R. W.; Pendleton, J. D. (1985) Dust generated by vehicular traffic on unpaved roadways: sizes and infrared extinction characteristics. *Aerosol Sci. Technol.* 4: 99-121.
- Pinnick, R. G.; Fernandez, G.; Martinez-Andazola, E.; Hinds, B. D.; Hansen, A. D. A.; Fuller, K. (1993) Aerosol in the arid southwestern United States: measurements of mass loading, volatility, size distribution, absorption characteristics, black carbon content, and vertical structure to 7 km above sea level. *J. Geophys. Res. [Atmos.]* 98: 2651-2666.
- Pires, M.; Rossi, M. J.; Ross, D. S. (1994) Kinetic and mechanistic aspects of the NO oxidation by O₂ in aqueous phase. *Int. J. Chem. Kinet.* 26: 1207-1227.
- Pitchford, M. L.; McMurry, P. H. (1994) Relationship between measured water vapor growth and chemistry of atmospheric aerosol for Grand Canyon, Arizona, in winter 1990. *Atmos. Environ.* 28: 827-839.
- Pitts, J. N., Jr.; Atkinson, R.; Sweetman, J. A.; Zielinska, B. (1985a) The gas-phase reaction of naphthalene with N₂O₅ to form nitronaphthalenes. *Atmos. Environ.* 19: 701-705.
- Pitts, J. N., Jr.; Zielinska, B.; Sweetman, J. A.; Atkinson, R.; Winer, A. M. (1985b) Reaction of adsorbed pyrene and perylene with gaseous N₂O₅ under simulated atmospheric conditions. *Atmos. Environ.* 19: 911-915.
- Pitts, J. N., Jr.; Paur, H.-R.; Zielinska, B.; Arey, J.; Winer, A. M.; Ramdahl, T.; Mejia, V. (1986) Factors influencing the reactivity of polycyclic aromatic hydrocarbons adsorbed on filters and ambient POM with ozone. *Chemosphere* 15: 675-685.
- Placet, M.; Battye, R. E.; Fehsenfeld, F. C.; Bassett, G. W. (1991) Emissions involved in acidic deposition processes. In: Irving, P. M., ed. *Acidic deposition: state of science and technology, volume I: emissions, atmospheric processes, and deposition*. Washington, DC: The U.S. National Acid Precipitation Assessment Program. (State of science and technology report no. 1).
- Pleim, J.; Venkatram, A.; Yamartino, R. J. (1984) *The dry deposition model, v. 4*. Rexdale, ON, Canada: Ontario Ministry of the Environment, ADOM/TADAP Model Development Program.
- Post, J. E.; Buseck, P. R. (1985) Quantitative energy-dispersive analysis of lead halide particles from the Phoenix urban aerosol. *Environ. Sci. Technol.* 19: 682-685.

- Pratsinis, S.; Ellis, E. C.; Novakov, T.; Friedlander, S. K. (1984) The carbon containing component of the Los Angeles aerosol: source apportionment and contributions to the visibility budget. *J. Air Pollut. Control Assoc.* 34: 643-650.
- Pratsinis, S. E.; Zeldin, M. D.; Ellis, E. C. (1988) Source resolution of the fine carbonaceous aerosol by principal component-stepwise regression analysis. *Environ. Sci. Technol.* 22: 212-216.
- Pruppacher, H. R.; Klett, J. D. (1980) *Microphysics of clouds and precipitation*. Boston, MA: D. Reidel Publishing Company.
- Pueschel, R. F.; Van Valin, C. C.; Castillo, R. C.; Kadlecsek, J. A.; Ganor, E. (1986) Aerosols in polluted versus nonpolluted air masses: long-range transport and effects on clouds. *J. Clim. Appl. Meteorol.* 25: 1908-1917.
- Rabano, E. S.; Castillo, N. T.; Torre, K. J.; Solomon, P. A. (1989) Speciation of arsenic in ambient aerosols collected in Los Angeles. *JAPCA* 39: 76-80.
- Rader, D. J.; McMurry, P. H. (1986) Application of the tandem differential mobility analyzer to studies of droplet growth or evaporation. *J. Aerosol Sci.* 17: 771-787.
- Radke, L. F.; Hobbs, P. V. (1991) Humidity and particle fields around some small cumulus clouds. *J. Atmos. Sci.* 48: 1190-1193.
- Radke, L. F.; Brock, C. A.; Lyons, J. H.; Hobbs, P. V.; Schnell, R. C. (1989) Aerosol and lidar measurements of hazes in mid-latitude and polar airmasses. *Atmos. Environ.* 23: 2417-2430.
- Raga, G. B.; Jonas, P. R. (1993) On the link between cloud-top radiative properties and sub-cloud aerosol concentrations. *Q. J. R. Meteorol. Soc.* 119: 1419-1425.
- Ramdahl, T. (1983) Polycyclic aromatic ketones in environmental samples. *Environ. Sci. Technol.* 17: 666-670.
- Ramdahl, T.; Becher, G.; Bjørseth, A. (1982) Nitrated polycyclic aromatic hydrocarbons in urban air particles. *Environ. Sci. Technol.* 16: 861-865.
- Ramdahl, T.; Bjørseth, A.; Lokensgard, D.; Pitts, J. N., Jr. (1984) Nitration of polycyclic aromatic hydrocarbons adsorbed to different carriers in a fluidized bed reactor. *Chemosphere* 13: 527-534.
- Ranade, M. B. (Arun); Woods, M. C.; Chen, F.-L.; Purdue, L. J.; Rehme, K. A. (1990) Wind tunnel evaluation of PM₁₀ samplers. *Aerosol Sci. Technol.* 13: 54-71.
- Rao, A. K.; Whitby, K. T. (1978) Non-ideal collection characteristics of inertial impactors—I. single-stage impactors and solid particles. *J. Aerosol Sci.* 9: 77-86.
- Rau, J. A. (1989) Composition and size distribution of residential wood smoke particles. *Aerosol Sci. Technol.* 10: 181-192.
- Reeks, M. W.; Reed, J.; Hall, D. (1988) On the resuspension of small particles by a turbulent flow. *J. Phys. D: Appl. Phys.* 21: 574-589.
- Richards, L. W. (1983) Comments on the oxidation of NO₂ to nitrate - day and night. *Atmos. Environ.* 17: 397-402.
- Richards, L. W.; Anderson, J. A.; Blumenthal, D. L.; Brandt, A. A.; McDonald, J. A.; Waters, N.; Macias, E. S.; Bhardwaja, P. S. (1981) The chemistry, aerosol physics, and optical properties of a western coal-fired power plant plume. *Atmos. Environ.* 15: 2111-2134.

- Richards, L. W.; Anderson, J. A.; Blumenthal, D. L.; McDonald, J. A. (1982a) Nitrogen and sulfur chemistry and aerosol formation in plumes. Presented at: 75th annual meeting of the Air Pollution Control Association; June; New Orleans, LA. Pittsburgh, PA: Air Pollution Control Association; paper no. 82-24.6.
- Richards, L. W.; Anderson, J. A.; Blumenthal, D. L.; McDonald, J. A. (1982b) Comparison of the optical properties of particles in smelter and western power plant plumes [poster presentation]. Presented at: 75th annual meeting of the Air Pollution Control Association; June; New Orleans, LA. Pittsburgh, PA: Air Pollution Control Association; poster presentation no. 82-7P.5
- Richards, L. W.; Blumenthal, D. L.; Bergstrom, R. W.; Seigneur, C.; Smith, T. B.; Macias, E. S.; Hering, S. V.; Bhardwaja, P. S.; Wilson, W. E. (1982c) VISTTA authors' reply. *Atmos. Environ.* 16: 2363-2365.
- Richards, L. W.; Anderson, J. A.; Blumenthal, D. L.; McDonald, J. A.; Macias, E. S.; Hering, S. V.; Wilson, W. E., Jr. (1985) Chemical, aerosol and optical measurements in the plumes of three midwestern coal-fired power plants. *Atmos. Environ.* 19: 1685-1704.
- Richards, L. W.; Blanchard, C. L.; Blumenthal, D. L. (1991) Navajo generating station visibility study, draft #2. Santa Rosa, CA: Sonoma Technology, Inc.; final report STI-90200-1124-FRD2.
- Richardson, C. B.; Hightower, R. L. (1987) Evaporation of ammonium nitrate particles. *Atmos. Environ.* 21: 971-975.
- Richardson, C. B.; Spann, J. F. (1984) Measurement of the water cycle in a levitated ammonium sulfate particle. *J. Aerosol Sci.* 15: 563-571.
- Roberts, D.; Williams, D. (1979) The kinetics of oxidation of sulphur dioxide within the plume from a sulphide smelter in a remote region. *Atmos. Environ.* 13: 1485-1499.
- Roelofs, G. J. H. (1992a) Drop size dependent sulfate distribution in a growing cloud. *J. Atmos. Chem.* 14: 109-118.
- Roelofs, G. J. H. (1992b) On the drop and aerosol size dependence of aqueous sulfate formation in a continental cumulus cloud. *Atmos. Environ. Part A* 26: 2309-2321.
- Roelofs, G. J. H. (1993) A cloud chemistry sensitivity study and comparison of explicit and bulk cloud model performance. *Atmos. Environ. Part A* 27: 2255-2264.
- Rogge, W. F.; Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1991) Sources of fine organic aerosol. 1. Charbroilers and meat cooking operations. *Environ. Sci. Technol.* 25: 1112-1125.
- Rogge, W. F.; Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1993a) Sources of fine organic aerosol. 2. Noncatalyst and catalyst-equipped automobiles and heavy-duty diesel trucks. *Environ. Sci. Technol.* 27: 636-651.
- Rogge, W. F.; Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1993b) Sources of fine organic aerosol. 3. Road dust, tire debris, and organometallic brake lining dust: roads as sources and sinks. *Environ. Sci. Technol.* 27: 1892-1904.
- Rogge, W. F.; Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1993c) Sources of fine organic aerosol. 4. Particulate abrasion products from leaf surfaces of urban plants. *Environ. Sci. Technol.* 27: 2700-2711.
- Rogge, W. F.; Mazurek, M. A.; Hildemann, L. M.; Cass, G. R.; Simoneit, B. R. T. (1993d) Quantification of urban organic aerosols at a molecular level: identification, abundance and seasonal variation. *Atmos. Environ. Part A* 27: 1309-1330.

- Rogge, W. F.; Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T. (1994) Sources of fine organic aerosol. 6. Cigarette smoke in the urban atmosphere. *Environ. Sci. Technol.* 28: 1375-1388.
- Rolph, G. D.; Draxler, R. R. (1990) Sensitivity of three-dimensional trajectories to the spatial and temporal densities of the wind field. *J. Appl. Meteorol.* 29: 1043-1054.
- Rood, M. J.; Larson, T. V.; Covert, D. S.; Ahlquist, N. C. (1985) Measurement of laboratory and ambient aerosols with temperature and humidity controlled nephelometry. *Atmos. Environ.* 19: 1181-1190.
- Rood, M. J.; Shaw, M. A.; Larson, T. V.; Covert, D. S. (1989) Ubiquitous nature of ambient metastable aerosol. *Nature (London)* 337: 537-539.
- Rounds, S. A.; Pankow, J. F. (1990) Application of a radial diffusion model to describe gas/particle sorption kinetics. *Environ. Sci. Technol.* 24: 1378-1386.
- Rubel, G. O.; Gentry, J. W. (1984) Measurement of the kinetics of solution droplets in the presence of adsorbed monolayers: determination of water accommodation coefficients. *J. Phys. Chem.* 88: 3142-3148.
- Sakugawa, H.; Kaplan, I. R.; Tsai, W.; Cohen, Y. (1990) Atmospheric hydrogen peroxide: does it share a role with ozone in degrading air quality? *Environ. Sci. Technol.* 24: 1452-1462.
- Satsumabayashi, H.; Kurita, H.; Yokouchi, Y.; Ueda, H. (1989) Mono- and di-carboxylic acids under long-range transport of air pollution in central Japan. *Tellus Ser. B* 41B: 219-229.
- Satsumakayashi, H.; Kurita, H.; Yokouchi, Y.; Ueda, H. (1990) Photochemical formation of particulate dicarboxylic acids under long-range transport in central Japan. *Atmos. Environ. Part A* 24: 1443-1450.
- Savoie, D. L.; Prospero, J. M.; Nees, R. T. (1987) Washout ratios of nitrate, non-sea-salt sulfate and sea-salt on Virginia Key, Florida and on American Samoa. *Atmos. Environ.* 21: 103-112.
- Saxena, P. (1994) Authors' response to comments on "Coupling thermodynamic theory with measurements to characterize acidity of atmospheric particles." *Aerosol Sci. Technol.* 20: 287-288.
- Saxena, V. K.; Hendler, A. H. (1983) In-cloud scavenging and resuspension of cloud active aerosols during winter storms over Lake Michigan. In: Pruppacher, H. R.; Semonin, R. G.; Slinn, W. G. N., eds. *Precipitation scavenging, dry deposition, and resuspension, v. 1: precipitation scavenging: proceedings of the fourth international conference; November-December 1982; Santa Monica, CA.* New York, NY: Elsevier; pp. 91-101.
- Saxena, P.; Hildemann, L. M. (1996) Water-soluble organics in atmospheric particles: a critical review of the literature and applications of thermodynamics to identify candidate compounds. *J. Atmos. Chem.*: accepted.
- Saxena, P.; Seigneur, C. (1987) On the oxidation of SO₂ to sulfate in atmospheric aerosols. *Atmos. Environ.* 21: 807-812.
- Saxena, P.; Mueller, P. K.; Kim, Y. P.; Seinfeld, J. H.; Koutrakis, P. (1993) Coupling thermodynamic theory with measurements to characterize acidity of atmospheric particles. *Aerosol Sci. Technol.* 19: 279-293.
- Saxena, P.; Hildemann, L. M.; McMurry, P. H.; Seinfeld, J. H. (1995) Organics alter hygroscopic behavior of atmospheric particles. *J. Geophys. Res. [Atmos.]*: in press.
- Saylor, R. D. (1989) A study of mesoscale acid deposition in the lower Ohio River Valley [Ph.D. dissertation]. Lexington, KY: University of Kentucky, Chemical Engineering Department.
- Schlesinger, R. B. (1994) Comments on "Coupling thermodynamic theory with measurements to characterize acidity of atmospheric particles" by P. Saxena et al. *Aerosol Sci. Technol.* 20: 285-286.

- Schmidt, J. A.; Andren, A. W. (1980) The atmospheric chemistry of nickel. In: Nriagu, J. O., ed. Nickel in the environment. New York, NY: John Wiley & Sons, Inc.; pp. 93-135.
- Schroeder, W. H.; Dobson, M.; Kane, D. M.; Johnson, N. D. (1987) Toxic trace elements associated with airborne particulate matter: a review. JAPCA 37: 1267-1285.
- Schuetzle, D.; Cronn, D.; Crittenden, A. L.; Charlson, R. J. (1975) Molecular composition of secondary aerosol and its possible origin. Environ. Sci. Technol. 9: 838-845.
- Schwartz, S. E. (1979) Residence times in reservoirs under non-steady-state conditions: application to atmospheric SO₂ and aerosol sulfate. Tellus 31: 530-547.
- Schwartz, S. E. (1984a) Gas-aqueous reactions of sulfur and nitrogen oxides in liquid-water clouds. In: Calvert, J. G., ed. SO₂, NO and NO₂ oxidation mechanisms: atmospheric considerations. Boston, MA: Butterworth Publishers; pp. 173-208. (Teasley, J. I., ed. Acid precipitation series: v. 3).
- Schwartz, S. E. (1984b) Gas- and aqueous-phase chemistry of HO₂ in liquid water clouds. J. Geophys. Res. [Atmos.] 89: 11,589-11,598.
- Schwartz, S. E. (1986a) Chemical conversions in clouds. In: Lee, S. D.; Schneider, T.; Grant, L. D.; Verkerk, P., eds. Aerosols: research, risk assessment and control strategies, proceedings of the second U.S.-Dutch international symposium; May 1985; Williamsburg, VA. Chelsea, MI: Lewis Publishers, Inc.; pp. 349-375.
- Schwartz, S. E. (1986b) Mass-transport considerations pertinent to aqueous-phase reactions of gases in liquid-water clouds. In: Jaeschke, W., ed. Chemistry of multiphase atmospheric systems. Berlin, Federal Republic of Germany: Springer-Verlag; pp. 415-471. (NATO advanced science institutes series G: ecological sciences v. 6).
- Schwartz, S. E. (1987) Both sides now: the chemistry of clouds. Ann. N. Y. Acad. Sci. 502: 83-144.
- Schwartz, S. E. (1988) Mass-transport limitation to the rate of in-cloud oxidation of SO₂: re-examination in the light of new data. Atmos. Environ. 22: 2491-2499.
- Schwartz, S. E. (1989) Acid deposition: unraveling a regional phenomenon. Science (Washington, DC) 243: 753-763.
- Schwartz, S. E.; Freiberg, J. E. (1981) Mass-transport limitation to the rate of reaction of gases in liquid droplets: application to oxidation of SO₂ in aqueous solutions. Atmos. Environ. 15: 1129-1144.
- Schwartz, S. E.; Newman, L. (1978) Processes limiting oxidation of sulfur dioxide in stack plumes. Environ. Sci. Technol. 12: 67-73.
- Schwartz, S. E.; Newman, L. (1983) Measurements of sulfate production in natural clouds [discussion of Hegg and Hobbs (1982)]. Atmos. Environ. 17: 2629-2632.
- Schwartz, S. E.; White, W. H. (1983) Kinetics of reactive dissolution of nitrogen oxides into aqueous solution. In: Schwartz, S. E., ed. Trace atmospheric constituents: properties, transformations, and fates. New York, NY: John Wiley & Sons; pp. 1-116. (Advances in environmental science and technology: v. 12).
- Scott, B. C.; Laulainen, N. S. (1979) On the concentration of sulfate in precipitation. J. Appl. Meteorol. 18: 138-147.
- Šega, K.; Fugaš, M. (1984) Seasonal and spatial differences in mass concentration levels and particle size distribution of aerosols over an urban area. Atmos. Environ. 18: 2433-2437.
- Sehmel, G. A. (1973) Particle resuspension from an asphalt road caused by car and truck traffic. Atmos. Environ. 7: 291-309.

- Sehmel, G. A. (1980) Particle and gas dry deposition: a review. *Atmos. Environ.* 14: 983-1011.
- Sehmel, G. A. (1984) Deposition and resuspension. In: Randerson, D., ed. *Atmospheric science and power production*. Washington, DC: U.S. Department of Energy, Office of Scientific and Technical Information; report no. DOE/TIC-27601; pp. 533-583. Available from: NTIS, Springfield, VA; DE84-005177.
- Seidl, W. (1989) Ionic concentrations and initial S(IV)-oxidation rates in droplets during the condensational stage of cloud. *Tellus Ser. B* 41B: 32-50.
- Seigneur, C. (1982) A model of sulfate aerosol dynamics in atmospheric plumes. *Atmos. Environ.* 16: 2207-2228.
- Seigneur, C.; Constantinou, E. (1995) Chemical kinetic mechanism for atmospheric chromium. *Environ. Sci. Technol.* 29: 222-231.
- Seigneur, C.; Saxena, P. (1984) A study of atmospheric acid formation in different environments. *Atmos. Environ.* 18: 2109-2124.
- Seigneur, C.; Saxena, P. (1988) A theoretical investigation of sulfate formation in clouds. *Atmos. Environ.* 22: 101-115.
- Seigneur, C.; Wegrecki, A. M. (1990) Mathematical modeling of cloud chemistry in the Los Angeles basin. *Atmos. Environ. Part A* 24: 989-1006.
- Seigneur, C.; Saxena, P.; Roth, P. M. (1984) Computer simulations of the atmospheric chemistry of sulfate and nitrate formation. *Science (Washington, DC)* 225: 1028-1030.
- Seinfeld, J. H.; Flagan, R. C.; Petti, T. B.; Stern, J. E.; Grosjean, D. (1987) *Aerosol formation in aromatic hydrocarbon-NOx systems*. Pasadena, CA: California Institute of Technology; project no. AP-6.
- Sergides, C. A.; Jassim, J. A.; Chughtai, A. R.; Smith, D. M. (1987) The structure of hexane soot. Part III: Ozonation studies. *Appl. Spectrosc.* 41: 482-492.
- Shah, J. J.; Johnson, R. L.; Heyerdahl, E. K.; Huntzicker, J. J. (1986) Carbonaceous aerosol at urban and rural sites in the United States. *J. Air Pollut. Control Assoc.* 36: 254-257.
- Shao, Y.; Raupach, M. R.; Findlater, P. A. (1993) Effect of saltation bombardment on the entrainment of dust by wind. *J. Geophys. Res. [Atmos.]* 98: 12,719-12,726.
- Shaw, M. A.; Rood, M. J. (1990) Measurement of the crystallization humidities of ambient aerosol particles. *Atmos. Environ. Part A* 24: 1837-1841.
- Sheridan, P. J.; Schnell, R. C.; Kahl, J. D.; Boatman, J. F.; Garvey, D. M. (1993) Microanalysis of the aerosol collected over south-central New Mexico during the ALIVE field experiment, May-December 1989. *Atmos. Environ. Part A* 27: 1169-1183.
- Shinn, J. H.; Homan, D. N.; Gay, D. D. (1983) Plutonium aerosol fluxes and pulmonary exposure rates during resuspension from bare soils near a chemical separation facility. In: Pruppacher, H. R.; Semonin, R. G.; Slinn, W. G. N., eds. *Precipitation scavenging, dry deposition, and resuspension, v. 2: dry deposition and resuspension: proceedings of the fourth international conference; November-December 1982; Santa Monica, CA*. New York, NY: Elsevier; pp. 1131-1143.
- Sievering, H.; Van Valin, C. C.; Barrett, E. W.; Pueschel, R. F. (1984) Cloud scavenging of aerosol sulfur: two case studies. *Atmos. Environ.* 18: 2685-2690.

- Sievering, H.; Boatman, J.; Galloway, J.; Keene, W.; Kim, Y.; Luria, M.; Ray, J. (1991) Heterogeneous sulfur conversion in sea-salt aerosol particles: the role of aerosol water content and size distribution. *Atmos. Environ. Part A* 25: 1479-1487.
- Sievering, H.; Gorman, E.; Kim, Y.; Ley, T.; Seidl, W.; Boatman, J. (1994) Heterogeneous conversion contribution to the sulfate observed over Lake Michigan. *Atmos. Environ.* 28: 367-370.
- Simoneit, B. R. T. (1984) Organic matter of the troposphere—III. characterization and sources of petroleum and pyrogenic residues in aerosols over the western United States. *Atmos. Environ.* 18: 51-67.
- Simoneit, B. R. T. (1986) Characterization of organic constituents in aerosols in relation to their origin and transport: a review. Presented at: the 2nd workshop on chemistry analysis of hydrocarbons in the environment; November 1985; Barcelona, Spain. *Int. J. Environ. Anal. Chem.* 23: 207-237.
- Simoneit, B. R. T. (1989) Organic matter of the troposphere - V: application of molecular marker analysis to biogenic emissions into the troposphere for source reconciliations. Presented at: the international symposium on biosphere-atmosphere exchange; March 1986; Mainz, Federal Republic of Germany. *J. Atmos. Chem.* 8: 251-275.
- Simoneit, B. R. T.; Mazurek, M. A. (1982) Organic matter of the troposphere—II. natural background of biogenic lipid matter in aerosols over the rural western United States. *Atmos. Environ.* 16: 2139-2159.
- Sisler, J. F.; Malm, W. C. (1994) The relative importance of soluble aerosols to spatial and seasonal trends of impaired visibility in the United States. *Atmos. Environ.* 28: 851-862.
- Sisterson, D. L.; Bowersox, V. C.; Olsen, A. R.; Meyers, T. P.; Olsen, A. R.; Vong, R. L. (1991) Deposition monitoring: methods and results. In: Irving, P. M., ed. *Acidic deposition: state of science and technology, volume I: emissions, atmospheric processes, and deposition*. Washington, DC: The U.S. National Acid Precipitation Assessment Program. (State of science and technology report no. 6).
- Slinn, W. G. N. (1983) Air-to-sea transfer of particles. In: Liss, P. S.; Slinn, W. G. N., eds. *Air-sea exchange of gases and particles*. Boston, MA: D. Reidel Publishing Company; pp. 299-405. (NATO ASI series. Series C, mathematical and physical sciences; no. 108).
- Sloane, C. S. (1982) Visibility trends—II. mideastern United States 1948-1978. *Atmos. Environ.* 16: 2309-2321.
- Sloane, C. S.; Groblicki, P. J. (1981) Denver's visibility history. *Atmos. Environ.* 15: 2631-2638.
- Sloane, C. S.; Watson, J.; Chow, J.; Pritchett, L.; Richards, L. W. (1991) Size-segregated fine particle measurements by chemical species and their impact on visibility impairment in Denver. *Atmos. Environ. Part A* 25: 1013-1024.
- Smith, T. B. (1981) Some observations of pollutant transport associated with elevated plumes. *Atmos. Environ.* 15: 2197-2203.
- Smith, D. M.; Akhter, M. S.; Jassim, J. A.; Sergides, C. A.; Welch, W. F.; Chughtai, A. R. (1989) Studies of the structure and reactivity of soot. *Aerosol Sci. Technol.* 10: 311-325.
- Snider, J. R.; Vali, G. (1994) Sulfur dioxide oxidation in winter orographic clouds. *J. Geophys. Res. [Atmos.]* 99: 18,713-18,733.
- Spann, J. F.; Richardson, C. B. (1985) Measurement of the water cycle in mixed ammonium acid sulfate particles. *Atmos. Environ.* 19: 819-825.

- Spengler, J. D.; Keeler, G. J.; Koutrakis, P.; Ryan, P. B.; Raizenne, M.; Franklin, C. A. (1989) Exposures to acidic aerosols. In: Symposium on the health effects of acid aerosols; October 1987; Research Triangle Park, NC. *Environ. Health Perspect.* 79: 43-51.
- Spicer, C. W. (1977a) Photochemical atmospheric pollutants derived from nitrogen oxides. *Atmos. Environ.* 11: 1089-1095.
- Spicer, C. W. (1977b) The fate of nitrogen oxides in the atmosphere. In: Pitts, J. N., Jr.; Metcalf, R. L.; Lloyd, A. C., eds. *Advances in environmental science and technology*: v. 4. New York, NY: John Wiley and Sons, Inc.; pp. 163-261.
- Stein, S. W.; Turpin, B. J.; Cai, X.; Huang, P.-F.; McMurry, P. H. (1994) Measurements of relative humidity-dependent bounce and density for atmospheric particles using the DMA-impactor technique. *Atmos. Environ.* 28: 1739-1746.
- Steiner, D.; Burtscher, H.; Gross, H. (1992) Structure and disposition of particles from a spark-ignition engine. *Atmos. Environ. Part A* 26: 997-1003.
- Stelson, A. W.; Seinfeld, J. H. (1981) Chemical mass accounting of urban aerosol. *Environ. Sci. Technol.* 15: 671-679.
- Stelson, A. W.; Seinfeld, J. H. (1982a) Relative humidity and temperature dependence of the ammonium nitrate dissociation constant. *Atmos. Environ.* 16: 983-992.
- Stelson, A. W.; Seinfeld, J. H. (1982b) Relative humidity and pH dependence of the vapor pressure of ammonium nitrate-nitric acid solutions at 25 °C. *Atmos. Environ.* 16: 993-1000.
- Stern, J. E.; Flagan, R. C.; Grosjean, D.; Seinfeld, J. H. (1987) Aerosol formation and growth in atmospheric aromatic hydrocarbon photooxidation. *Environ. Sci. Technol.* 21: 1224-1231.
- Stevens, R. K.; Dzubay, T. G.; Lewis, C. W.; Shaw, R. W., Jr. (1984) Source apportionment methods applied to the determination of the origin of ambient aerosols that affect visibility in forested areas. *Atmos. Environ.* 18: 261-272.
- Stewart, D. A.; Liu, M.-K. (1981) Development and application of a reactive plume model. *Atmos. Environ.* 15: 2377-2393.
- Storey, J. M. E.; Pankow, J. F. (1992) Gas-particle partitioning of semi-volatile organic compounds to model atmospheric particulate materials—I. Sorption to graphite, sodium chloride, alumina, and silica particles under low humidity conditions. *Atmos. Environ. Part A* 26: 435-443.
- Strapp, J. W.; Leaitch, W. R.; Anlauf, K. G.; Bottenheim, J. W.; Joe, P.; Schemenauer, R. S.; Wiebe, H. A.; Isaac, G. A.; Kelly, T. J.; Daum, P. H. (1988) Winter cloud water and air composition in Central Ontario. *J. Geophys. Res. [Atmos.]* 93: 3760-3772.
- Suh, H. H.; Spengler, J. D.; Koutrakis, P. (1992) Personal exposures to acid aerosols and ammonia. *Environ. Sci. Technol.* 26: 2507-2517.
- Suh, H. H.; Allen, G. A.; Aurian-Blăjeni, B.; Koutrakis, P.; Burton, R. M. (1994a) Field method comparison for the characterization of acid aerosols and gases. *Atmos. Environ.* 28: 2981-2989.
- Suh, H. H.; Koutrakis, P.; Spengler, J. D. (1994b) The relationship between airborne acidity and ammonia in indoor environments. *J. Exposure Anal. Environ. Epidemiol.* 4: 1-23.
- Suh, H. H.; Allen, G. A.; Koutrakis, P.; Burton, R. M. (1995) Spatial variation in acidic sulfate and ammonia concentrations within metropolitan Philadelphia. *J. Air Waste Manage. Assoc.* 45: 442-452.

- Sutherland, A. J. (1967) Proposed mechanism for sediment entrainment by turbulent flows. *J. Geophys. Res.* 72: 6183-6194.
- Svenningsson, B.; Hansson, H.-C.; Wiedensohler, A.; Noone, K.; Ogren, J.; Hallberg, A.; Calvile, R. (1994) Hygroscopic growth of aerosol particles and its influence on nucleation scavenging in cloud: experimental results from Kleiner Feldberg. *J. Atmos. Chem.* 19: 129-152.
- Sverdrup, G. M.; Whitby, K. T. (1980) The effect of changing relative humidity on aerosol size distribution measurements. In: Hidy, G. M.; Mueller, P. K.; Grosjean, D.; Appel, B. R.; Wesolowski, J. J., eds. *The character and origins of smog aerosols: a digest of results from the California Aerosol Characterization Experiment (ACHEX)*. New York, NY: John Wiley & Sons; pp. 527-558. (Advances in environmental science and technology: v. 10).
- Sviridenkov, M. A.; Gillette, D. A.; Isakov, A. A.; Sokolik, I. N.; Smirnov, V. V.; Belan, B. D.; Pachenko, M. V.; Andronova, A. V.; Kolomiets, S. M.; Zhukov, V. M.; Zhukovsky, D. A. (1993) Size distributions of dust aerosol measured during the Soviet-American experiment in Tadzhikistan, 1989. *Atmos. Environ. Part A* 27: 2481-2486.
- TSI. (1993) Model 390045 DISTFITTM aerosol data fitting software. St. Paul and Golden Valley, MN: TSI, Inc. and Chimera Software.
- Tang, I. N. (1980) Deliquescence properties and particle size change of hygroscopic aerosols. In: Willeke, K., ed. *Generation of aerosols and facilities for exposure experiments*. Ann Arbor, MI: Ann Arbor Science; pp. 153-167.
- Tang, I. N.; Munkelwitz, H. R. (1977) Aerosol growth studies—III. ammonium bisulfate aerosols in a moist atmosphere. *J. Aerosol Sci.* 8: 321-330.
- Tang, I. N.; Munkelwitz, H. R. (1993) Composition and temperature dependence of the deliquescence properties of hygroscopic aerosols. *Atmos. Environ. Part A* 27: 467-473.
- Tang, I. N.; Munkelwitz, H. R. (1994) Water activities, densities, and refractive indices of aqueous sulfates and sodium nitrate droplets of atmospheric importance. *J. Geophys. Res. [Atmos.]* 99: 18,801-18,808.
- Tang, I. N.; Munkelwitz, H. R.; Davis, J. G. (1978) Aerosol growth studies - IV. phase transformation of mixed salt aerosols in a moist atmosphere. *J. Aerosol Sci.* 9: 505-511.
- Tang, I. N.; Wong, W. T.; Munkelwitz, H. R. (1981) The relative importance of atmospheric sulfates and nitrates in visibility reduction. *Atmos. Environ.* 15: 2463-2471.
- Tani, B.; Siegel, S.; Johnson, S. A.; Kumar, R. (1983) X-ray diffraction investigation of atmospheric aerosols in the 0.3-1.0 μm aerodynamic size range. *Atmos. Environ.* 17: 2277-2283.
- Tao, Y.; McMurry, P. H. (1989) Vapor pressures and surface free energies of C14-C18 monocarboxylic acids and C5 and C6 dicarboxylic acids. *Environ. Sci. Technol.* 23: 1519-1523.
- Taylor, G. I. (1922) Diffusion by continuous movements. *Proc. London Math. Soc.* 20: 196-212.
- Taylor, G. R. (1989) Sulfate production and deposition in midlatitude continental cumulus clouds. Part II: Chemistry model formulation and sensitivity analysis. *J. Atmos. Sci.* 46: 1991-2007.
- Ten Brink, H. M.; Schwartz, S. E.; Daum, P. H. (1987) Efficient scavenging of aerosol sulfate by liquid-water clouds. *Atmos. Environ.* 21: 2035-2052.

- Thibodeaux, L. J.; Nadler, K. C.; Valsaraj, K. T.; Reible, D. D. (1991) The effect of moisture on volatile organic chemical gas-to-particle partitioning with atmospheric aerosols—competitive adsorption theory predictions. *Atmos. Environ. Part A* 25: 1649-1656.
- Thomas, P.; Vogt, S. (1990) Mesoscale atmospheric dispersion experiments using tracer and tetroons. *Atmos. Environ. Part A* 24: 1271-1284.
- Thompson, K. M.; Koutrakis, P.; Brauer, M.; Spengler, J. D.; Wilson, W. E.; Burton, R. M. (1991) Measurements of aerosol acidity: sampling frequency, seasonal variability, and spatial variation. Presented at: 84th annual meeting and exhibition of the Air & Waste Management Association; June; Vancouver, BC, Canada. Pittsburgh, PA: Air & Waste Management Association; paper no. 91-89.5.
- Thurston, G. D.; Gorczynski, J. E., Jr.; Jaques, P.; Currie, J.; He, D. (1992) An automated sequential sampling system for particulate acid aerosols: description, characterization, and field sampling results. *J. Exposure Anal. Environ. Epidemiol.* 2: 415-428.
- Tuazon, E. C.; Atkinson, R.; Plum, C. N.; Winer, A. M.; Pitts, J. N., Jr. (1983) The reaction of gas phase N_2O_5 with water vapor. *Geophys. Res. Lett.* 10: 953-956.
- Turpin, B. J.; Huntzicker, J. J. (1991) Secondary formation of organic aerosol in the Los Angeles basin: a descriptive analysis of organic and elemental carbon concentrations. *Atmos. Environ. Part A* 25: 207-215.
- Turpin, B. J.; Huntzicker, J. J. (1995) Identification of secondary organic aerosol episodes and quantitation of primary and secondary organic aerosol concentrations during SCAQS. *Atmos. Environ.* 29: 3527-3544.
- Turpin, B. J.; Cary, R. A.; Huntzicker, J. J. (1990) An in situ, time-resolved analyzer for aerosol organic and elemental carbon. *Aerosol Sci. Technol.* 12: 161-171.
- Turpin, B. J.; Huntzicker, J. J.; Larson, S. M.; Cass, G. R. (1991) Los Angeles summer midday particulate carbon: primary and secondary aerosol. *Environ. Sci. Technol.* 25: 1788-1793.
- Turpin, B. J.; Liu, S.-P.; Podolske, K. S.; Gomes, M. S. P.; Eisenreich, S. J.; McMurry, P. H. (1993) Design and evaluation of a novel diffusion separator for measuring gas/particle distributions of semivolatile organic compounds. *Environ. Sci. Technol.* 27: 2441-2449.
- Twohy, C. H.; Austin, P. H.; Charlson, R. J. (1989) Chemical consequences of the initial diffusional growth of cloud droplets: a clean marine case. *Tellus Ser. B* 41B: 51-60.
- Twomey, S. (1959) The nuclei of natural cloud formation: part II: the supersaturation in natural clouds and the variation of cloud droplet concentration. *Geofis. Pura Appl.* 43: 243-249.
- U.S. Environmental Protection Agency. (1982) Air quality criteria for particulate matter and sulfur oxides. Research Triangle Park, NC: Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office; EPA report no. EPA-600/8-82-029aF-cF. 3v. Available from: NTIS, Springfield, VA; PB84-156777.
- U.S. Environmental Protection Agency. (1986a) Health assessment document for nickel and nickel compounds. Research Triangle Park, NC: Environmental Criteria and Assessment Office; report no. EPA/600/8-83/012FF. Available from: NTIS, Springfield, VA; PB86-232212.
- U.S. Environmental Protection Agency. (1986b) Air quality criteria for lead. Research Triangle Park, NC: Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office; EPA report no. EPA-600/8-83/028aF-dF. 4v. Available from: NTIS, Springfield, VA; PB87-142378.

- U.S. Environmental Protection Agency. (1995) Compilation of air pollutant emission factors, v. I: stationary point and area sources. 5th ed. Research Triangle Park, NC: Office of Air Quality Planning and Standards; sections 1.1 and 1.2; report no. AP-42.
- Uliasz, M. (1993) The atmospheric mesoscale dispersion modeling system. *J. Appl. Meteorol.* 32: 139-149.
- Valerio, F.; Bottino, P.; Ugolini, D.; Cimberle, M. R.; Tozzi, G. A.; Frigerio, A. (1984) Chemical and photochemical degradation of polycyclic aromatic hydrocarbons in the atmosphere. *Sci. Total Environ.* 40: 169-188.
- Valsaraj, K. T.; Thoma, G. J.; Reible, D. D.; Thibodeaux, L. J. (1993) On the enrichment of hydrophobic organic compounds in fog droplets. *Atmos. Environ. Part A* 27: 203-210.
- Van Borm, W. A.; Adams, F. C.; Maenhaut, W. (1989) Characterization of individual particles in the Antwerp aerosol. *Atmos. Environ.* 23: 1139-1151.
- Vanderpool, R. W.; Lundgren, D. A.; Marple, V. A.; Rubow, K. L. (1987) Cocalibration of four large-particle impactors. *Aerosol Sci. Technol.* 7: 177-185.
- Van Doren, J. M.; Watson, L. R.; Davidovits, P.; Worsnop, D. R.; Zahniser, M. S.; Kolb, C. E. (1990) Temperature dependence of the uptake coefficients of HNO_3 , HCl , and N_2O_5 by water droplets. *J. Phys. Chem.* 94: 3265-3272.
- Van Grieken, R.; Xhoffer, C. (1992) Microanalysis of individual environmental particles. *J. Anal. At. Spectrom.* 7: 81-88.
- Van Valin, C. C.; Luria, M.; Ray, J. D.; Boatman, J. F. (1990) Hydrogen peroxide and ozone over the northeastern United States in June 1987. *J. Geophys. Res. [Atmos.]* 95: 5689-5695.
- Venkataraman, C.; Friedlander, S. K. (1994) Size distributions of polycyclic aromatic hydrocarbons and elemental carbon. 2. Ambient measurements and effects of atmospheric processes. *Environ. Sci. Technol.* 28: 563-572.
- Venkataraman, C.; Hildemann, L. M. (1994) Factors affecting the distribution of primary semivolatile organic compounds of urban aerosol particles. *Environ. Sci. Technol.*: submitted.
- Venkataraman, C.; Lyons, J. M.; Friedlander, S. K. (1994) Size distributions of polycyclic aromatic hydrocarbons and elemental carbon. 1. Sampling, measurement methods, and source characterization. *Environ. Sci. Technol.* 28: 555-562.
- Wagman, J.; Lee, R. E., Jr.; Axt, C. J. (1967) Influence of some atmospheric variables on the concentration and particle size distribution of sulfate in urban air. *Atmos. Environ.* 1: 479-489.
- Walcek, C. J.; Stockwell, W. R.; Chang, J. S. (1990) Theoretical estimates of the dynamic, radiative and chemical effects of clouds on tropospheric trace gases. *Atmos. Res.* 25: 53-69.
- Waldman, J. M.; Liou, P. J.; Thurston, G. D.; Lippmann, M. (1990) Spatial and temporal patterns in summertime sulfate aerosol acidity and neutralization within a metropolitan area. *Atmos. Environ. Part B* 24: 115-126.
- Waldman, J. M.; Koutrakis, P.; Allen, G. A.; Thurston, G. D.; Burton, R. M.; Wilson, W. E. (1995) Human exposures to particle strong acidity. In: Phalen, R. F.; Bates, D. V., eds. *Proceedings of the colloquium on particulate air pollution and human mortality and morbidity, part II*; January 1994; Irvine, CA. *Inhalation Toxicol.* 7: 657-669.
- Wall, S. M.; John, W.; Ondo, J. L. (1988) Measurement of aerosol size distributions for nitrate and major ionic species. *Atmos. Environ.* 22: 1649-1656.

- Wang, C.; Chang, J. S. (1993) A three-dimensional numerical model of cloud dynamics, microphysics, and chemistry: 4. cloud chemistry and precipitation chemistry. *J. Geophys. Res. [Atmos.]* 98: 16,799-16,808.
- Wang, H.-C.; John, W. (1987) Comparative bounce properties of particle materials. *Aerosol Sci. Technol.* 7: 285-299.
- Wang, H.-C.; John, W. (1988) Characteristics of the Berner impactor for sampling inorganic ions. *Aerosol Sci. Technol.* 8: 157-172.
- Wang, S.-C.; Paulson, S. E.; Grosjean, D.; Flagan, R. C.; Seinfeld, J. H. (1992a) Aerosol formation and growth in atmospheric organic/NO_x systems—I. Outdoor smog chamber studies of C₇- and C₈- hydrocarbons. *Atmos. Environ. Part A* 26: 403-420.
- Wang, S.-C.; Flagan, R. C.; Seinfeld, J. H. (1992b) Aerosol formation and growth in atmospheric organic/NO_x systems—II. aerosol dynamics. *Atmos. Environ. Part A* 26: 421-434.
- Warner, T. T. (1981) Verification of a three-dimensional transport model using tetroon data from Project STATE. *Atmos. Environ.* 15: 2219-2222.
- Warren, R. S.; Birch, P. (1987) Heavy metal levels in atmospheric particulates, roadside dust and soil along a major urban highway. *Sci. Total Environ.* 59: 253-256.
- Watson, J. G.; Chow, J. C. (1992) Data bases for PM₁₀ and PM_{2.5} chemical compositions and source profiles. *Transactions AWMA* 1: 61-91.
- Watson, J. G.; Chow, J. C.; Lurmann, F. W.; Musarra, S. P. (1994a) Ammonium nitrate, nitric acid, and ammonia equilibrium in wintertime Phoenix, Arizona. *Air Waste* 44: 405-412.
- Watson, J. G.; Chow, J. C.; Lu, Z.; Fujita, E. M.; Lowenthal, D. H.; Lawson, D. R.; Ashbaugh, L. L. (1994b) Chemical mass balance source apportionment of PM₁₀ during the Southern California Air Quality Study. *Aerosol Sci. Technol.* 21: 1-36.
- Weathers, K. C.; Likens, G. E.; Bormann, F. H.; Bicknell, S. H.; Bormann, B. T.; Daube, B. C., Jr.; Eaton, J. S.; Galloway, J. N.; Keene, W. C.; Kimball, K. D.; McDowell, W. H.; Siccama, T. G.; Smiley, D.; Tarrant, R. A. (1988) Cloudwater chemistry from ten sites in North America. *Environ. Sci. Technol.* 22: 1018-1026.
- Weber, R. J.; McMurry, P. H.; Eisele, F. L.; Tanner, D. J. (1995) Measurement of expected nucleation precursor species and 5 to 500 nm diameter particles at Mauna Loa, Hawaii. *J. Atmos. Sci.* 52: 2242-2257.
- Wesely, M. L.; Hicks, B. B. (1977) Some factors that affect the deposition rates of sulfur dioxide and similar gases on vegetation. *J. Air Pollut. Control Assoc.* 27: 1110-1116.
- Wexler, A. S.; Seinfeld, J. H. (1990) The distribution of ammonium salts among a size and composition dispersed aerosol. *Atmos. Environ. Part A* 24: 1231-1246.
- Wexler, A. S.; Seinfeld, J. H. (1992) Analysis of aerosol ammonium nitrate: departures from equilibrium during SCAQS. *Atmos. Environ. Part A* 26: 579-591.
- Wexler, A. S.; Eldering, A.; Pandis, S. N.; Cass, G. R.; Seinfeld, J. H.; Moon, K. C.; Hering, S. (1992) Modeling aerosol processes and visibility based on the SCAQS data. Final report. Sacramento, CA: California Air Resources Board; contract no. A932-054.
- Whitby, K. T. (1978) The physical characteristics of sulfur aerosols. *Atmos. Environ.* 12: 135-159.
- Whitby, K. T. (1980) Aerosol formation in urban plumes. *Ann. N. Y. Acad. Sci.* 338: 258-275.

- Whitby, K. T. (1984) Physical and optical behavior of sulfate-nitrate aerosols in equilibrium with atmospheric water vapor, ammonia and nitric acid. In: Ruhnke, L. H.; Deepak, A., eds. Hygroscopic aerosols: technical proceedings of the workshop on hygroscopic aerosols in the planetary boundary layer; April 1982; Vail, CO. Hampton, VA: A. Deepak Publishing; pp. 45-63.
- Whitby, K. T.; Sverdrup, G. M. (1980) California aerosols: their physical and chemical characteristics. In: Hidy, G. M.; Mueller, P. K.; Grosjean, D.; Appel, B. R.; Wesolowski, J. J., eds. The character and origins of smog aerosols: a digest of results from the California Aerosol Characterization Experiment (ACHEX). New York, NY: John Wiley & Sons, Inc.; pp. 477-517. (Advances in environmental science and technology: v. 9).
- Whitby, K. T.; Husar, R. B.; Liu, B. Y. H. (1972) The aerosol size distribution of Los Angeles smog. *J. Colloid Interface Sci.* 39: 177-204.
- Whitby, K. T.; Charlson, R. E.; Wilson, W. E.; Stevens, R. K. (1974) The size of suspended particle matter in air. *Science* (Washington, DC) 183: 1098-1099.
- White, W. H.; Macias, E. S. (1989) Carbonaceous particles and regional haze in the western United States. *Aerosol Sci. Technol.* 10: 111-117.
- White, W. H.; Anderson, J. A.; Blumenthal, D. L.; Husar, R. B.; Gillani, N. V.; Husar, J. D.; Wilson, W. E., Jr. (1976) Formation and transport of secondary air pollutants: ozone and aerosols in the St. Louis urban plume. *Science* (Washington, DC) 194: 187-189.
- White, W. H.; Patterson, D. E.; Wilson, W. E. (1983) Urban exports to the nonurban troposphere: results from Project MISTT. *J. Geophys. Res.* 88: 10,745-10,752.
- White, W. H.; Seigneur, C.; Heinold, D. W.; Eltgroth, M. W.; Richards, L. W.; Roberts, P. T.; Bhardwaja, P. S.; Conner, W. D.; Wilson, W. E., Jr. (1985) Predicting the visibility of chimney plumes: an intercomparison of four models with observations at a well-controlled power plant. *Atmos. Environ.* 19: 515-528.
- Wiedensohler, A.; Aalto, P.; Covert, D.; Heintzenberg, J.; McMurry, P. H. (1994) Intercomparison of four methods to determine size distributions of low-concentration ($\sim 100 \text{ cm}^{-3}$), ultrafine aerosols ($3 < D_p < 10 \text{ nm}$) with illustrative data from the Arctic. *Aerosol Sci. Technol.* 21: 95-109.
- Willeke, K.; Whitby, K. T. (1975) Atmospheric aerosols: size distribution interpretation. *J. Air Pollut. Control Assoc.* 25: 529-534.
- Willets, B. (1992) [Personal communication]. Aberdeen, Scotland: University of Aberdeen.
- Williams, D. J.; Carras, J. N.; Milne, J. W.; Heggie, A. C. (1981) The oxidation and long-range transport of sulphur dioxide in a remote region. *Atmos. Environ.* 15: 2255-2262.
- Wilson, W. E. (1978) Sulfates in the atmosphere: a progress report on project MISTT. *Atmos. Environ.* 12: 537-547.
- Wilson, W. E., Jr. (1981) Sulfate formation in point source plumes: a review of recent field studies. *Atmos. Environ.* 15: 2573-2581.
- Wilson, J. C.; McMurry, P. H. (1981) Studies of aerosol formation in power plant plumes—II. secondary aerosol formation in the Navajo generating station plume. In: White, W. H.; Moore, D. J.; Lodge, J. P., eds. Plumes and visibility: measurements and model components: proceedings of the symposium; November 1980; Grand Canyon National Park, AZ. *Atmos. Environ.* 15: 2329-2339.
- Wilson, W. E.; Suh, H. H. (1996) Fine and coarse particles: concentration relationships relevant to epidemiological studies. *J. Air Waste Manage. Assoc.*: accepted.

- Wilson, W. E.; Spiller, L. L.; Ellestad, T. G.; Lamothe, P. J.; Dzubay, T. G.; Stevens, R. K.; Macias, E. S.; Fletcher, R. A.; Husar, J. D.; Husar, R. B.; Whitby, K. T.; Kittelson, D. B.; Cantrell, B. K. (1977) General Motors sulfate dispersion experiment: summary of EPA measurements. *J. Air Pollut. Control Assoc.* 27: 46-51.
- Wilson, J. C.; Gupta, A.; Whitby, K. T.; Wilson, W. E. (1988) Measured aerosol light scattering coefficients compared with values calculated from EAA and optical particle counter measurements: improving the utility of the comparison. *Atmos. Environ.* 22: 789-793.
- Winklmayr, W.; Wang, H.-C.; John, W. (1990) Adaptation of the Twomey algorithm to the inversion of cascade impactor data. *Aerosol Sci. Technol.* 13: 322-331.
- Wolff, G. T. (1981) Particulate elemental carbon in the atmosphere. *J. Air Pollut. Control Assoc.* 31: 935-938.
- Wolff, G. T.; Korsog, P. E. (1985) Estimates of the contributions of sources to inhalable particulate concentrations in Detroit. *Atmos. Environ.* 19: 1399-1409.
- Wolff, G. T.; Lioy, P. J.; Wight, G. D.; Meyers, R. E.; Cederwall, R. T. (1977) An investigation of long-range transport of ozone across the midwestern and eastern United States. *Atmos. Environ.* 11: 797-802.
- Wolff, G. T.; Groblicki, P. J.; Cadle, S. H.; Countess, R. J. (1982) Particulate carbon at various locations in the United States. In: Wolff, G. T.; Klimsch, R. L., eds. *Particulate carbon: atmospheric life cycle*. New York, NY: Plenum Press; pp. 297-315.
- Wolff, G. T.; Ruthkosky, M. S.; Stroup, D. P.; Korsog, P. E. (1991) A characterization of the principal PM-10 species in Claremont (summer) and Long Beach (fall) during SCAQS. *Atmos. Environ. Part A* 25: 2173-2186.
- Wu, P.-M.; Okada, K. (1994) Nature of coarse nitrate particles in the atmosphere—a single particle approach. *Atmos. Environ.* 28: 2053-2060.
- Yamartino, R. J.; Scire, J. S.; Carmichael, G. R.; Chang, Y. S. (1992) The CALGRID mesoscale photochemical grid model—I. Model formulation. *Atmos. Environ. Part A* 26: 1493-1512.
- Yamasaki, H.; Kuwata, K.; Miyamoto, H. (1982) Effects of ambient temperature on aspects of airborne polycyclic aromatic hydrocarbons. *Environ. Sci. Technol.* 16: 189-194.
- Zafiriou, O. C.; Gagosian, R. B.; Peltzer, E. T.; Alford, J. B.; Loder, T. (1985) Air-to-sea fluxes of lipids at Enewetak Atoll. *J. Geophys. Res. [Atmos.]* 90: 2409-2423.
- Zhang, X.; McMurry, P. H. (1991) Theoretical analysis of evaporative losses of adsorbed or absorbed species during atmospheric aerosol sampling. *Environ. Sci. Technol.* 25: 456-469.
- Zhang, S.-H.; Shaw, M.; Seinfeld, J. H.; Flagan, R. C. (1992) Photochemical aerosol formation from α -pinene and β -pinene. *J. Geophys. Res. [Atmos.]* 97: 20,717-20,729.
- Zhang, X. Q.; McMurry, P. H.; Hering, S. V.; Casuccio, G. S. (1993) Mixing characteristics and water content of submicron aerosols measured in Los Angeles and at the Grand Canyon. *Atmos. Environ. Part A* 27: 1593-1607.
- Zhang, J.; Wilson, W. E.; Lioy, P. J. (1994) Indoor air chemistry: formation of organic acids and aldehydes. *Environ. Sci. Technol.* 28: 1975-1982.
- Zimmerman, P. R. (1979) Testing of hydrocarbon emissions from vegetation, leaf litter and aquatic surfaces, and development of a methodology for compiling biogenic emission inventories: final report. Research Triangle Park, NC: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards; EPA report no. EPA-450/4-79-004. Available from: NTIS, Springfield, VA; PB-296070.

Zwozdziak, J. W.; Zwozdziak, A. B. (1990) Sulphate aerosol production in the upper parts of the Sudety Range, Poland. J. Aerosol Sci. 21(suppl. 1): S369-S372.